EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

What advanced accelerators could do and possible beam parameters for high energies

Ralph W. Aßmann, Coordinator EuPRAXIA, DESY & INFN

IFAST Workshop

Valencia, Spain

30 March – 1 April 2022

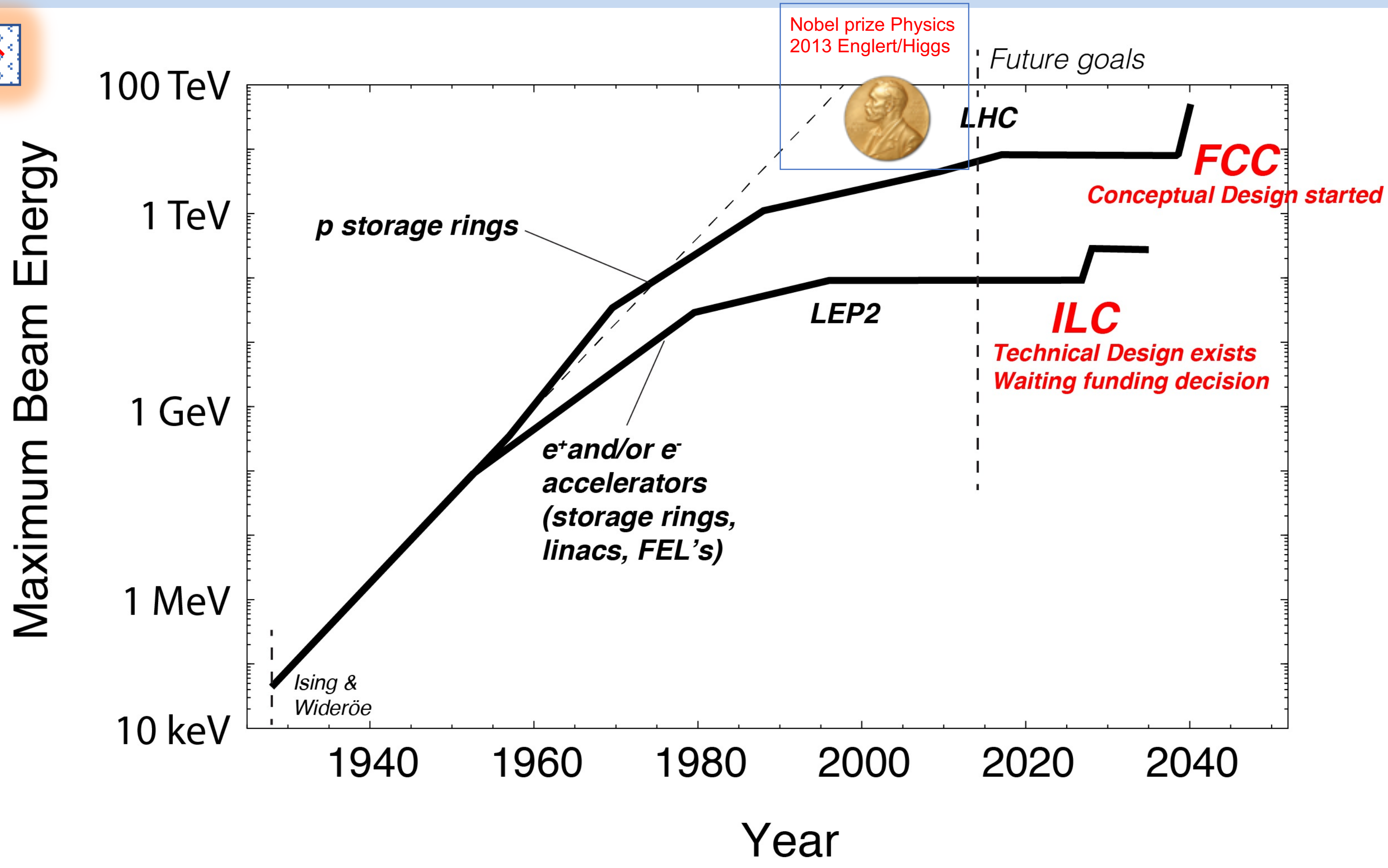
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 653782.

Outline

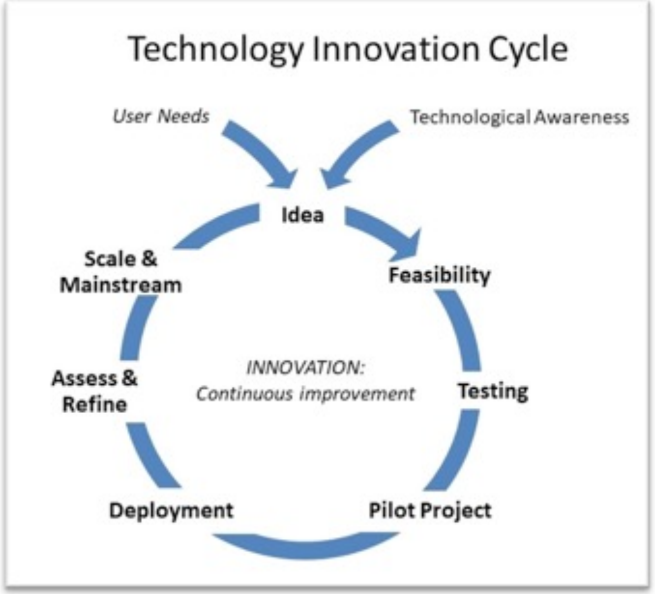
Horizon 2020

- **The Plasma Accelerator Context**
- The EuPRAXIA Objective
- ESFRI and EuPRAXIA
- EuPRAXIA as a User Facility
- EuPRAXIA Implementation
- EuPRAXIA Innovation
- EuPRAXIA ESFRI Features
- Towards Particle Physics
- Conclusion

Livingston Curve: Success of RF Accelerators



Examples of **new ideas and solutions**: RF, AG focusing, beta squeeze, stochastic cooling, polarized beams, super-conducting magnets/RF, advanced materials for vacuum/collimators, plasma / laser accelerators, …



A. Walter Dorn, Unite Paper 2021(1)
https://walterdorn.net/home/295-tech-innovation-model-for-un-2

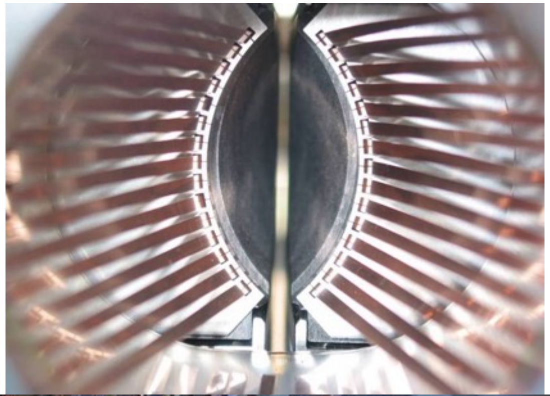
Master-pieces of technology: LHC, LHC HiLumi, SuperKEKb, DAFNE, LEP, LEP-2, Tevatron, HERA, RHIC, SLC, Eu-XFEL, SwissFEL, SACLA, ESRF-EBS, …

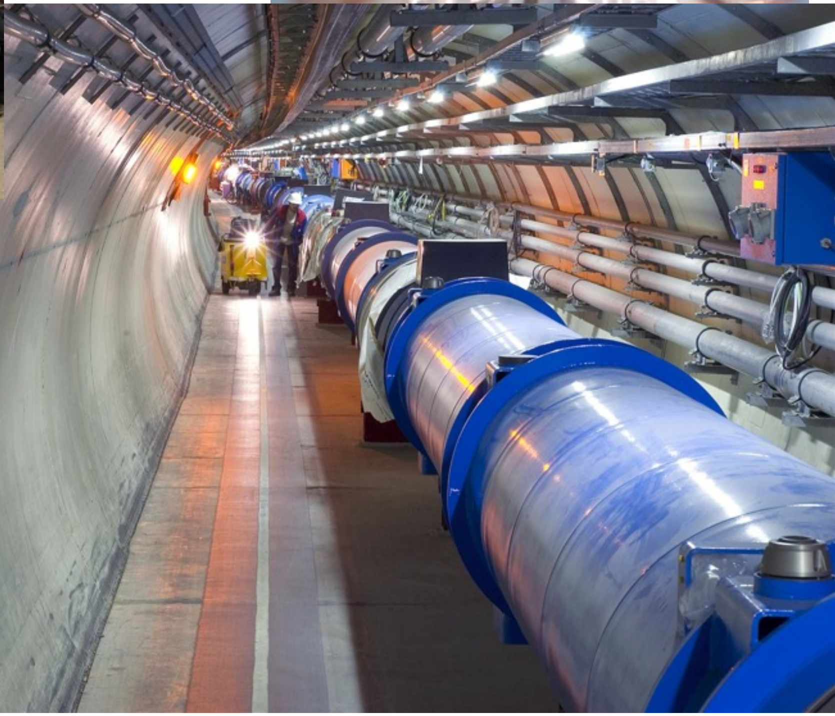
LHC as a Masterpiece of Accelerator Science

80 Years after the first RF accelerator in Aachen and 48 Years after Touschek`s e^+e^- Collider at Frascati

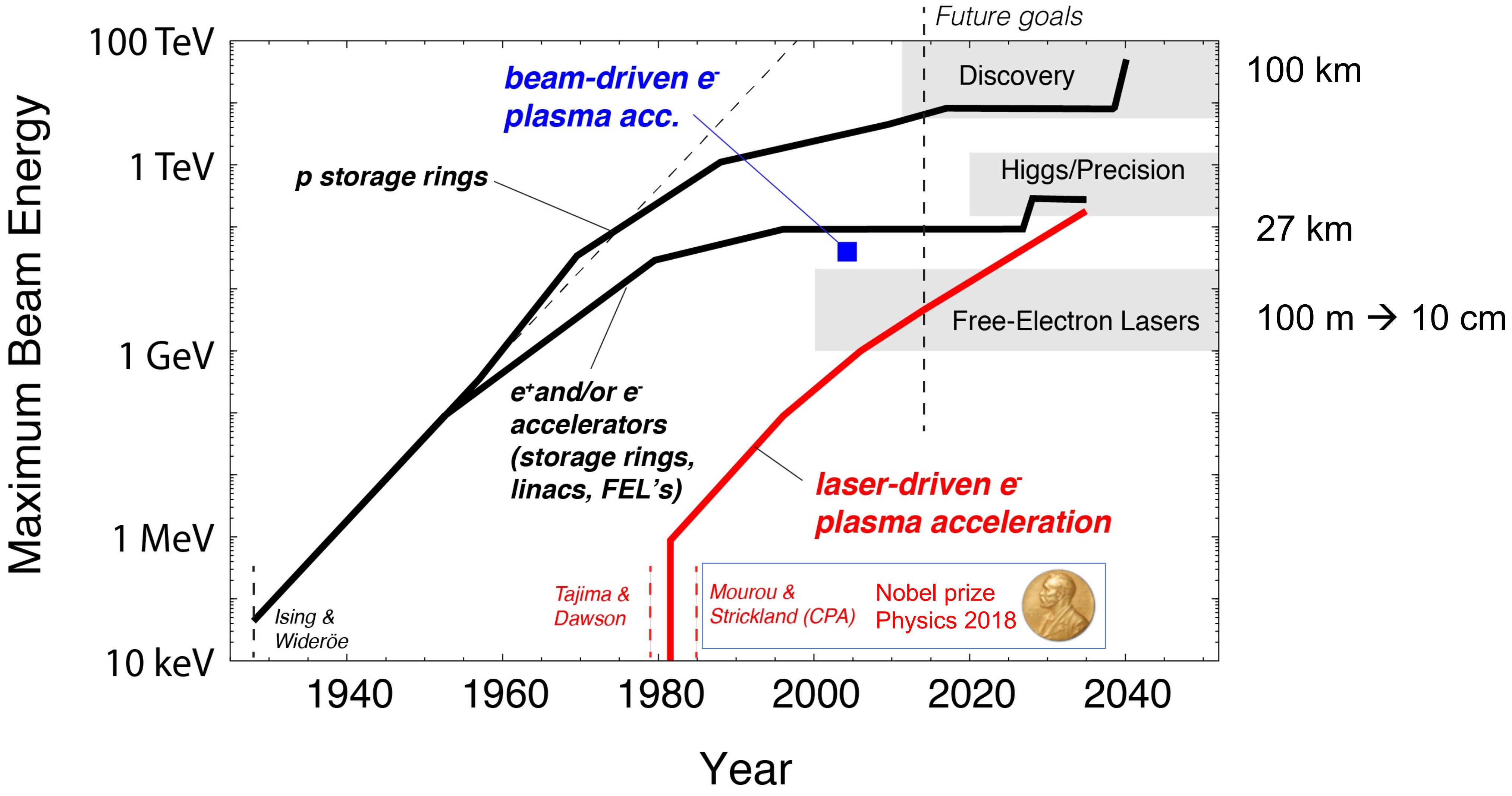
First beam
10.9. 2008

Higgs
Sem.
4.7.
2012

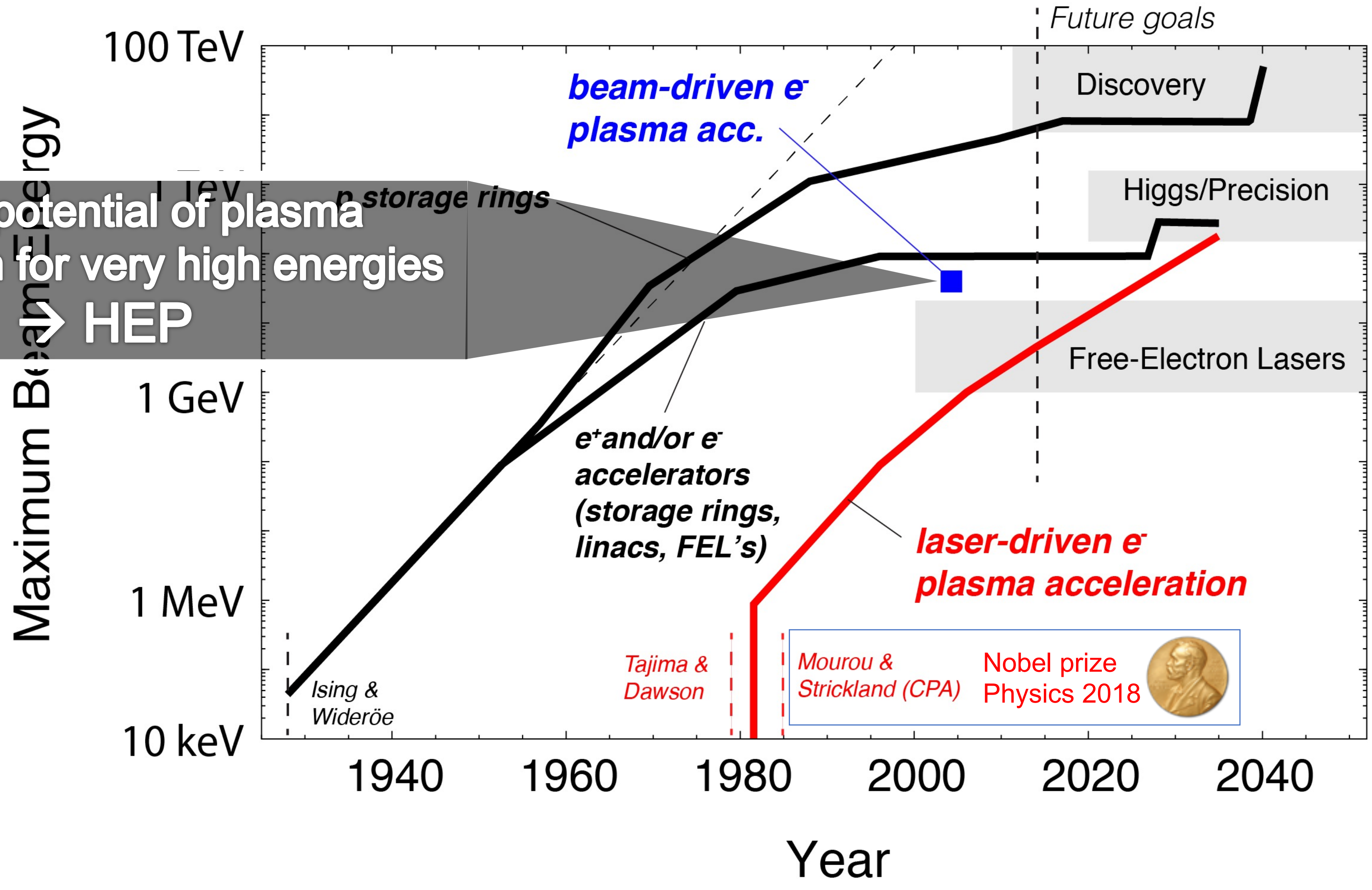




The Plasma Accelerator Opportunity



The Plasma Accelerator Opportunity



Shows potential of plasma acceleration for very high energies

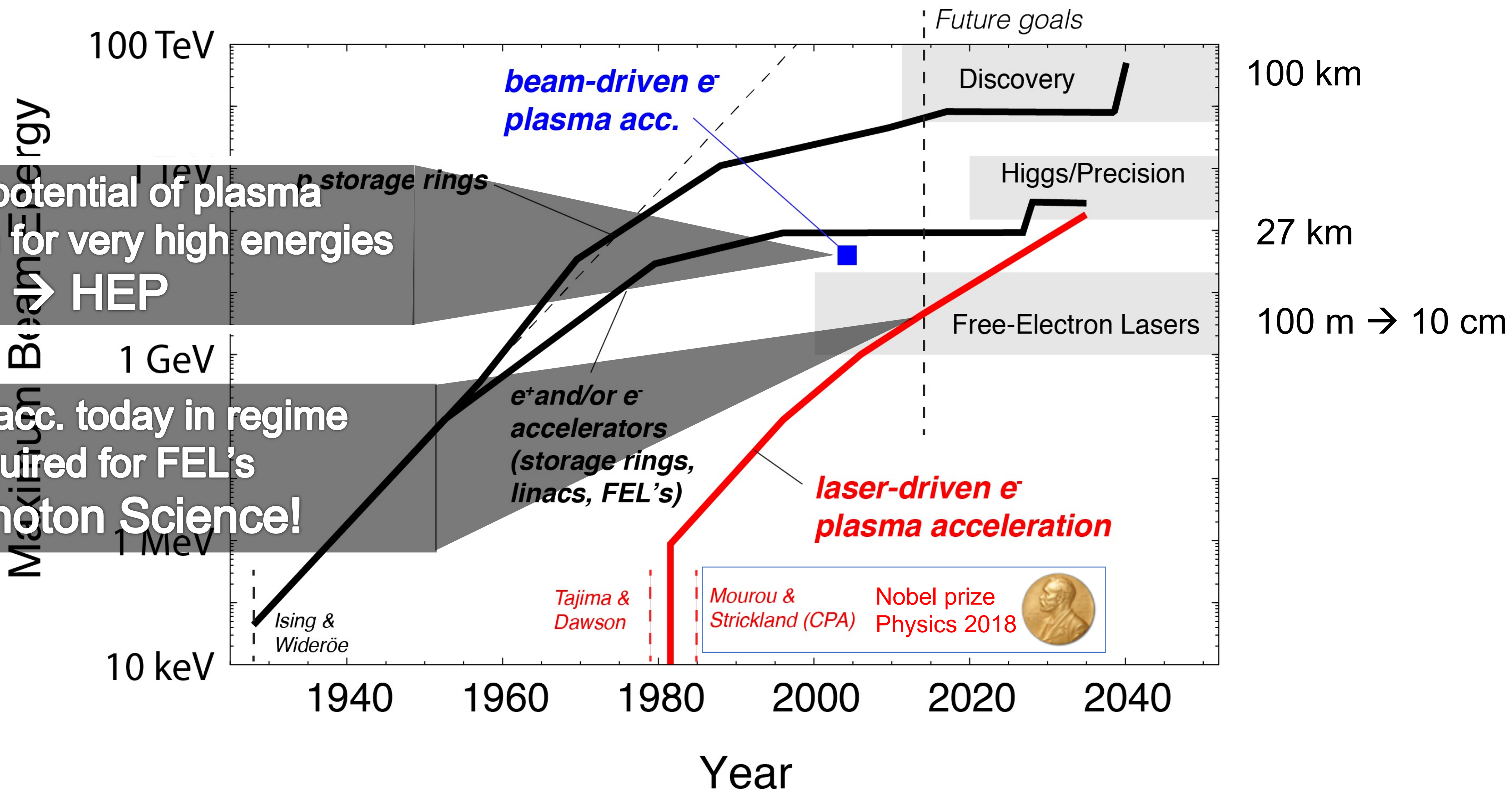
→ HEP

100 km

27 km

100 m → 10 cm

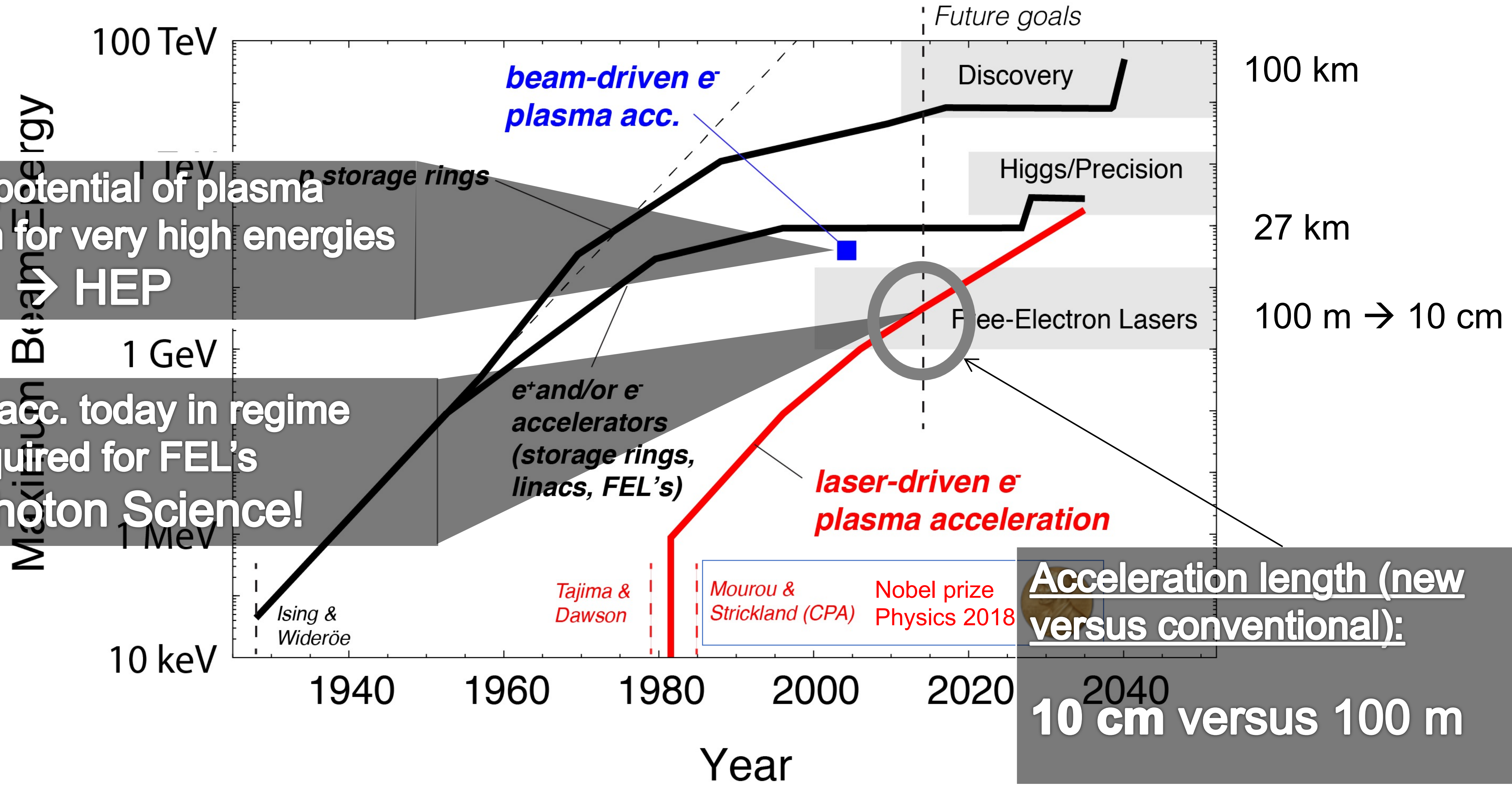
The Plasma Accelerator Opportunity



Shows potential of plasma acceleration for very high energies
→ HEP

Plasma acc. today in regime required for FEL's
→ Photon Science!

The Plasma Accelerator Opportunity



Shows potential of plasma acceleration for very high energies → HEP

Plasma acc. today in regime required for FEL's → Photon Science!

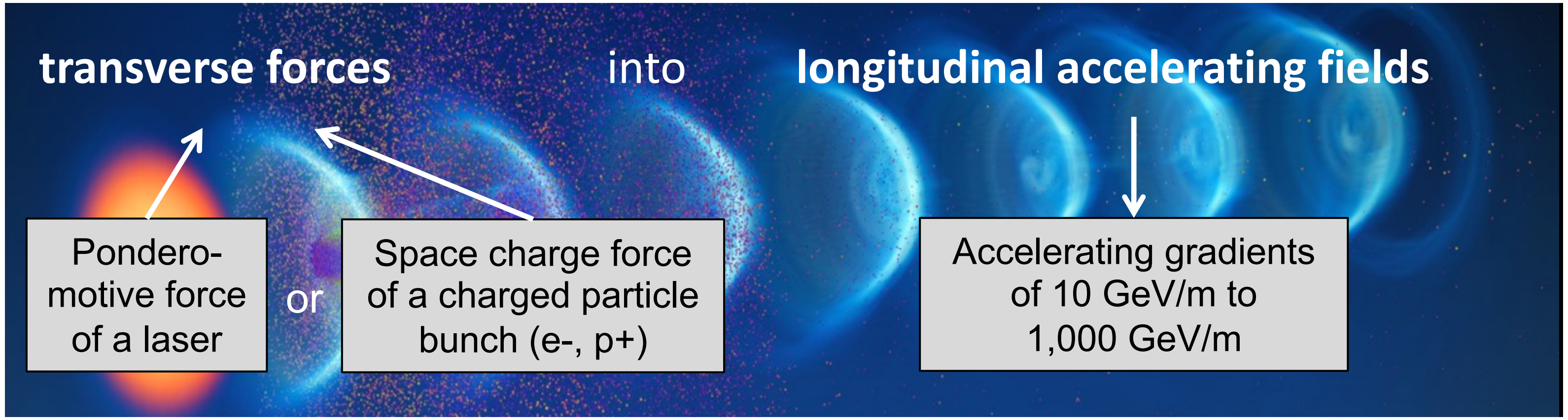
Acceleration length (new versus conventional):

10 cm versus 100 m

Reminder: The Principle

Overcome high-field limitations of metallic walls with dynamic plasma structures (undestructible)

Ground-breaking idea in 1979 by Tajima and Dawson: Wakefields inside a homogenous plasma can convert



transverse forces into **longitudinal accelerating fields**

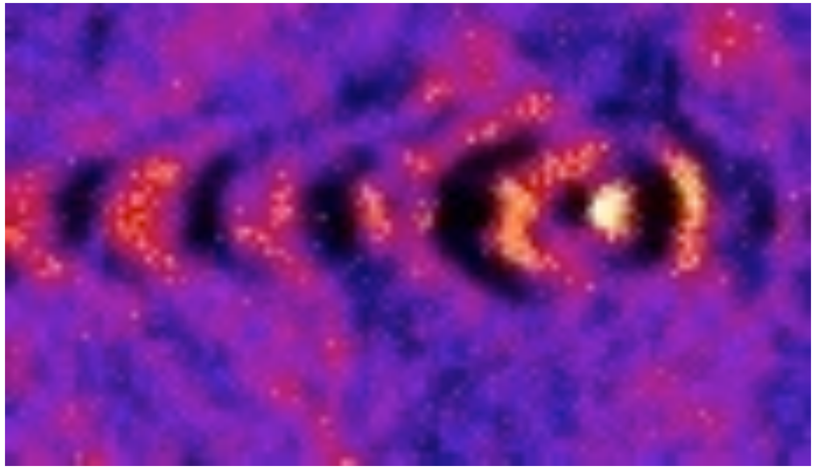
Pondero-motive force of a laser

or

Space charge force of a charged particle bunch (e-, p+)

Accelerating gradients of 10 GeV/m to 1,000 GeV/m

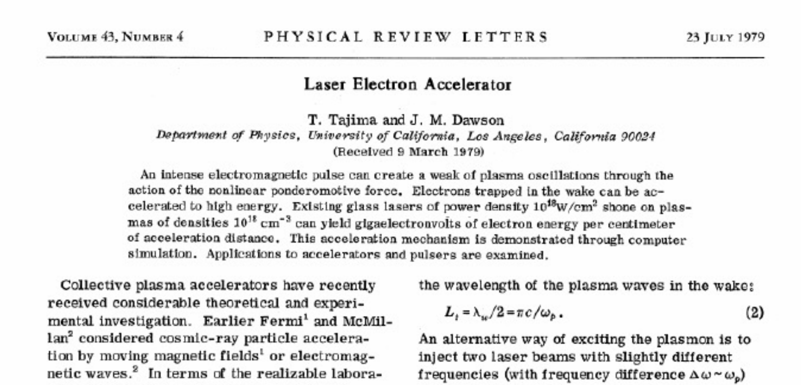
Picture from PhD A. Ferran Pousa



Wakefield photo courtesy M. Kaluza

Options for driving wakefields:

Lasers:	Industrially available, steep progress, path to low cost Limited energy per drive pulse (up to **50 J**)
Electron bunch:	Short bunches (need μm) available, need long RF accelerator More energy per drive pulse (up to **500 J**)
Proton bunch:	Only long (inefficient) bunches, need very long RF accelerator Maximum energy per drive pulse (up to **100,000 J**)



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators,

the wavelength of the plasma waves in the wake:

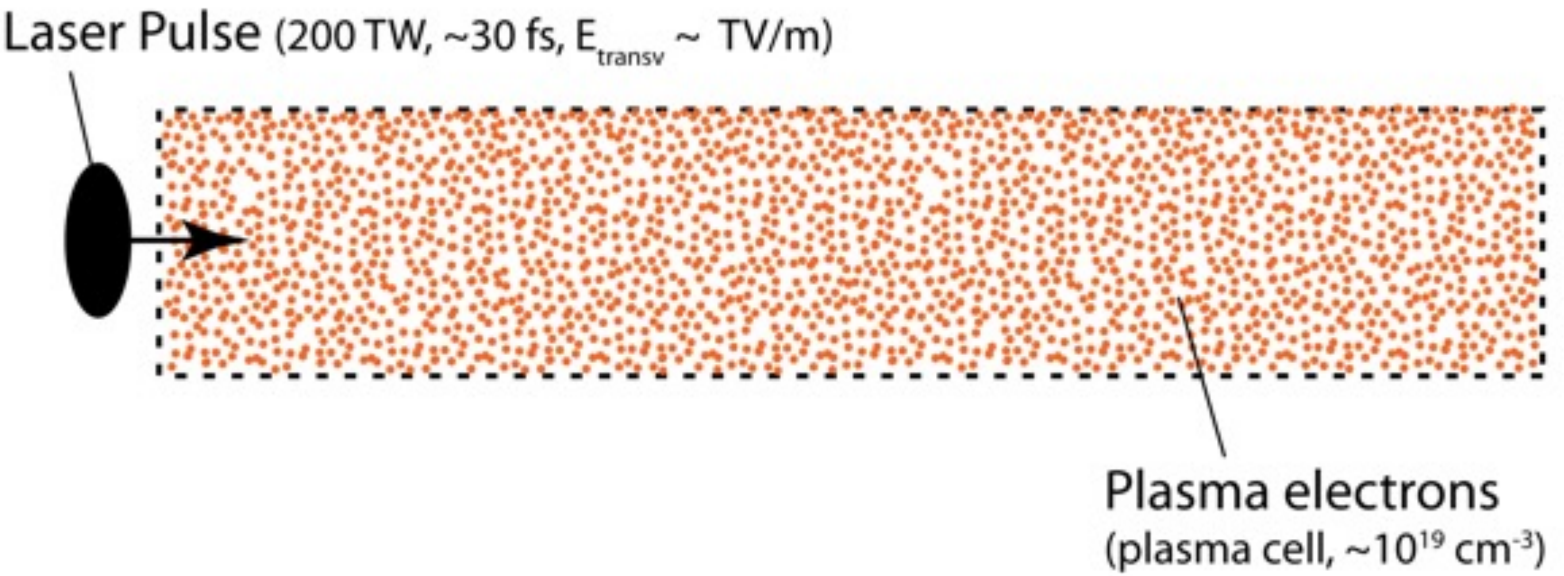
$$L_t = \lambda_w/2 = \pi c/\omega_p . \quad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes

Reminder: The Principle

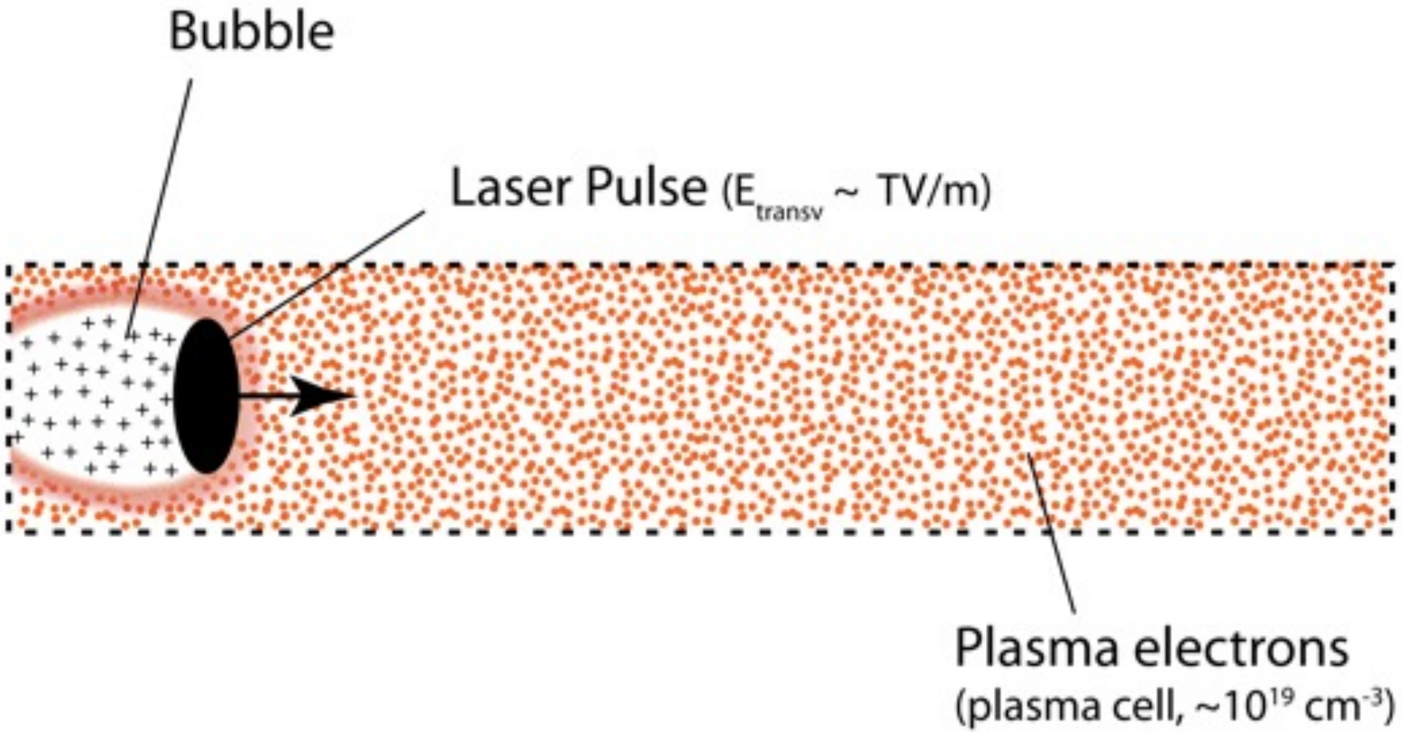
Internal injection

Works the same way with an **electron beam as wakefield driver**. But then usually lower plasma density. Ponderomotive force of laser is then replaced with space charge force of electrons on plasma electrons (repelling).



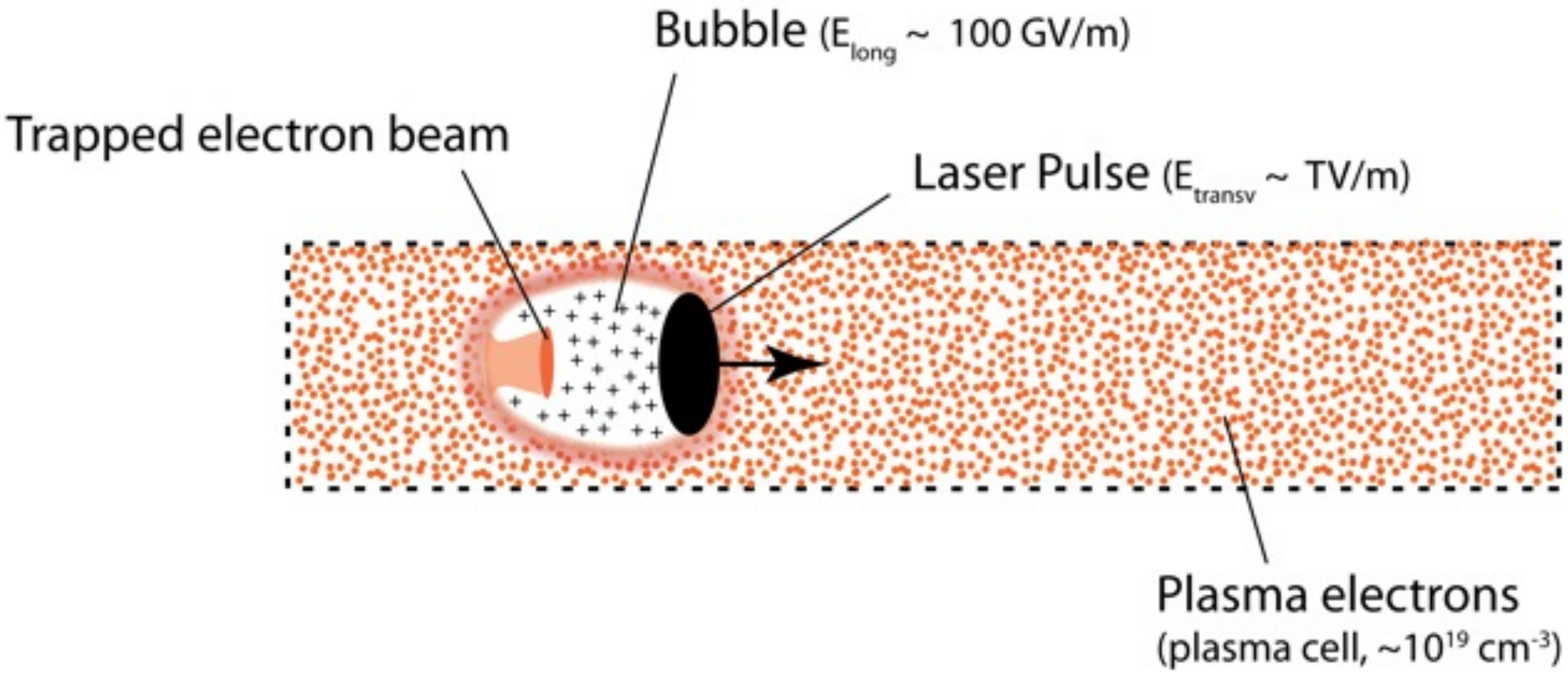
Reminder: The Principle

Internal injection



Reminder: The Principle

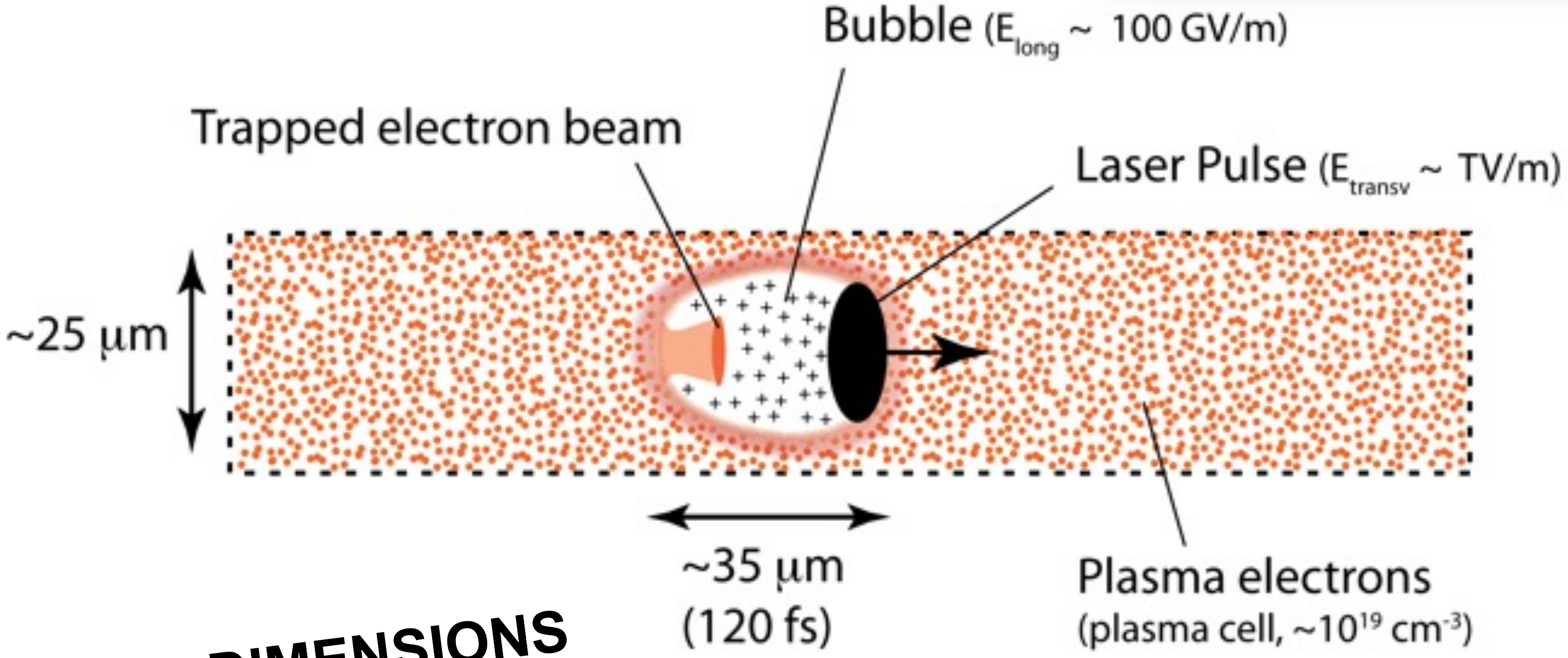
Internal injection



Reminder: The Principle

Internal injection

This accelerator fits into a human hair

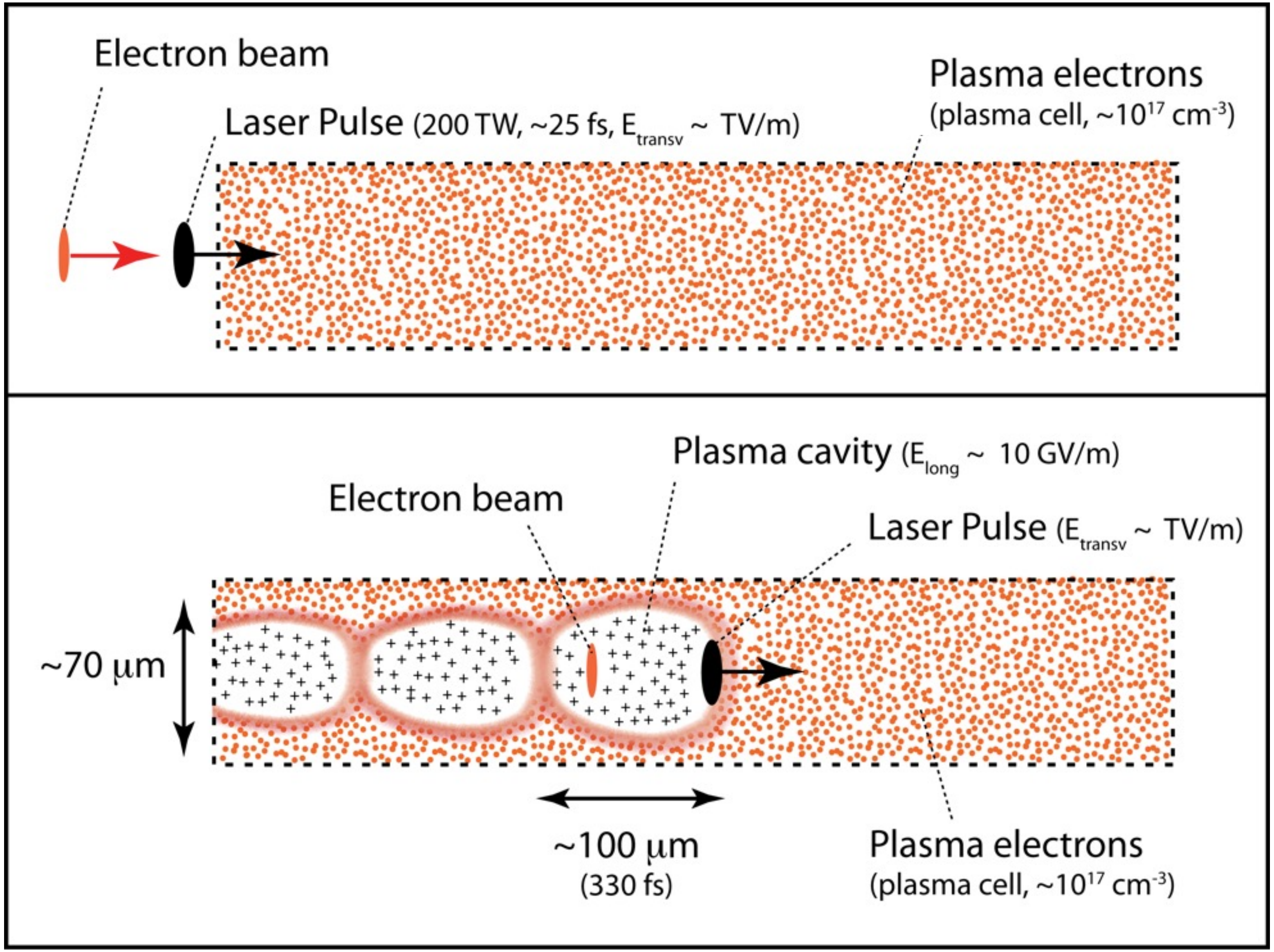


or particle pulse as driver

SMALL DIMENSIONS

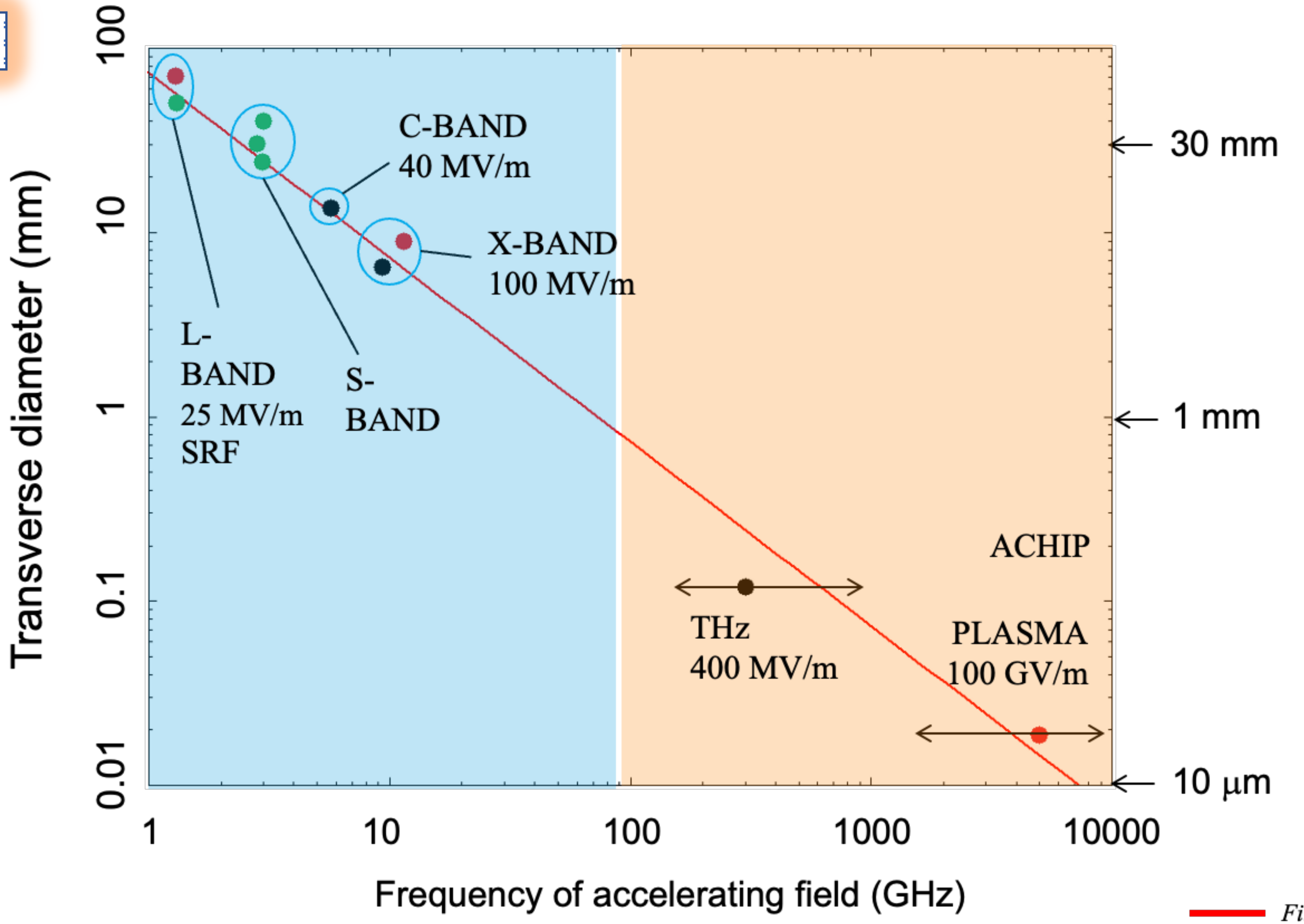
Reminder: The Principle

External injection



SMALL DIMENSIONS

Shrinking Down the Bucket Volume



Metallic RF regime:

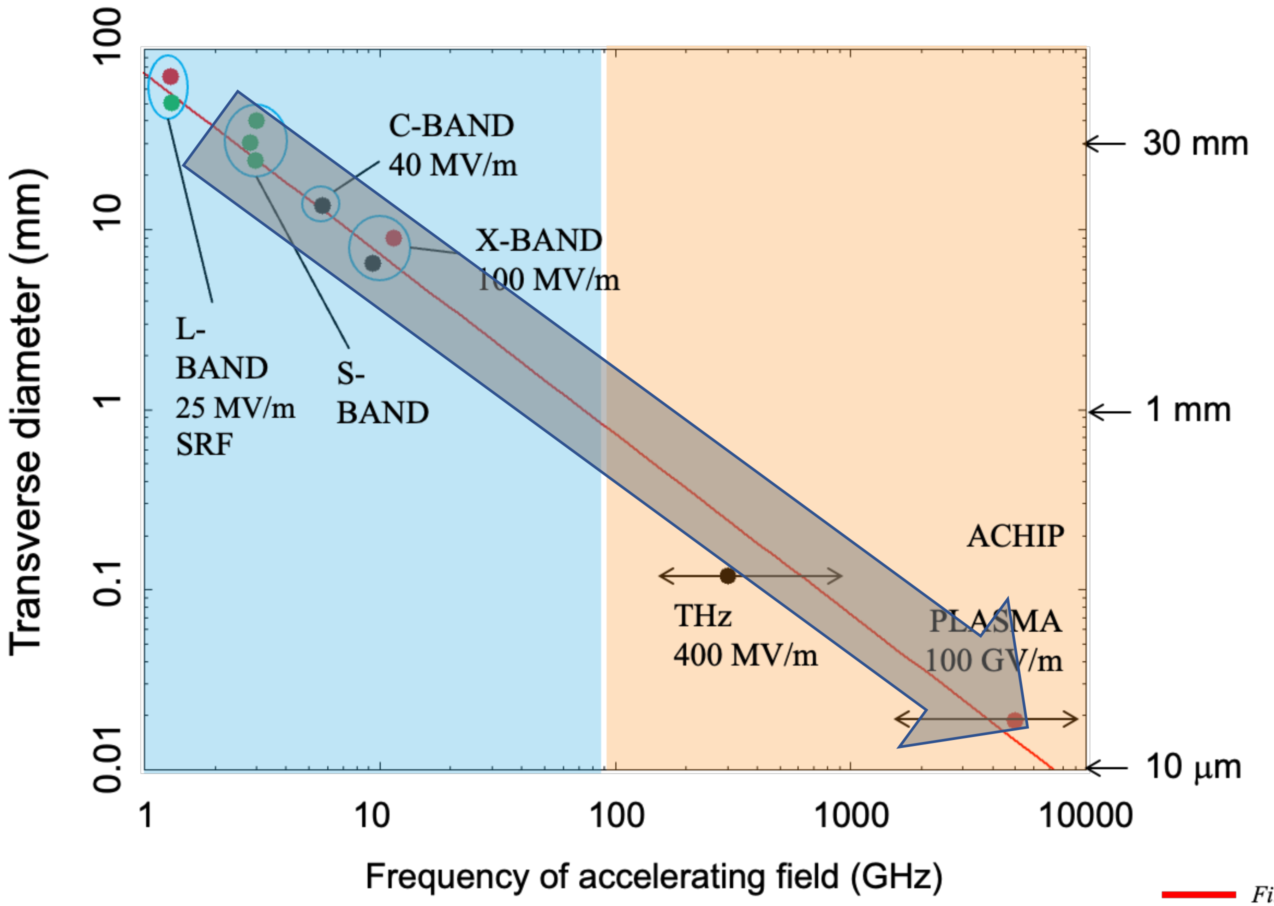
- **SRF**: High quality, high average power acceleration, long trains → CW
- **S/X band**: Generate high brightness beams for all purposes, ultra-fast science and diagnostics, injector for novel accelerators

Novel regime:

- Novel drivers, in particular **high tech lasers** for compact photon science and medical applications.
- **RF beam drivers** mainly for HEP or other high average power.
- **Compact** foot-print, low pulse charge, **high repetition rate**.
- **Challenges of micro and nano dimensions** – assess with modern tools (synergy with ultra-fast).

Fit based on the analytical law for the cavity diameter with the TM_{010} mode divided by π

Shrinking Down the Bucket Volume



Fit based on the analytical law for the cavity diameter with the TM_{010} mode divided by π

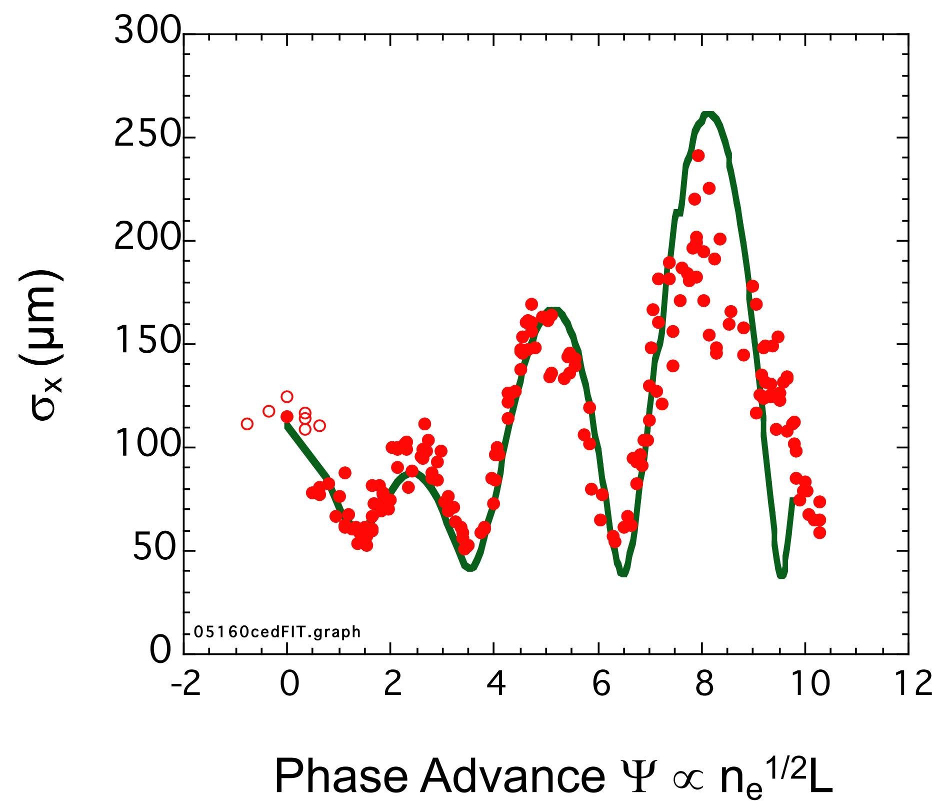
- for electrons: **factor 10^9 reduction** in volume of accelerating bucket from S band to plasma regime
- more difficult to fit high population electron bunches into small volume – limitations from various effects, helped by strong focusing for electrons
- particular problem for an advanced collider: luminosity scales with the square of the bunch charge: limits luminosity and efficiency
- **Very critical: Maximum electron charge?**
- even much more serious for positrons: even smaller volume and defocusing problem

Timely to Build Something Useful

- Particle accelerators are a fascinating research topic but define their **purpose through producing usable beams** for important research or applications.
- **RF based particle accelerators serve about 70,000 users** in science, enabling discoveries, advances in human knowledge.
- Plasma particle accelerators have made **great progress** but have not served in a user facility so far.
- “Emerging since 40 years”: timely to **demonstrate first user applications before end of 2020`s** (within 50 years of idea).
- Basic R&D can continue in parallel but we should focus on usable beam.

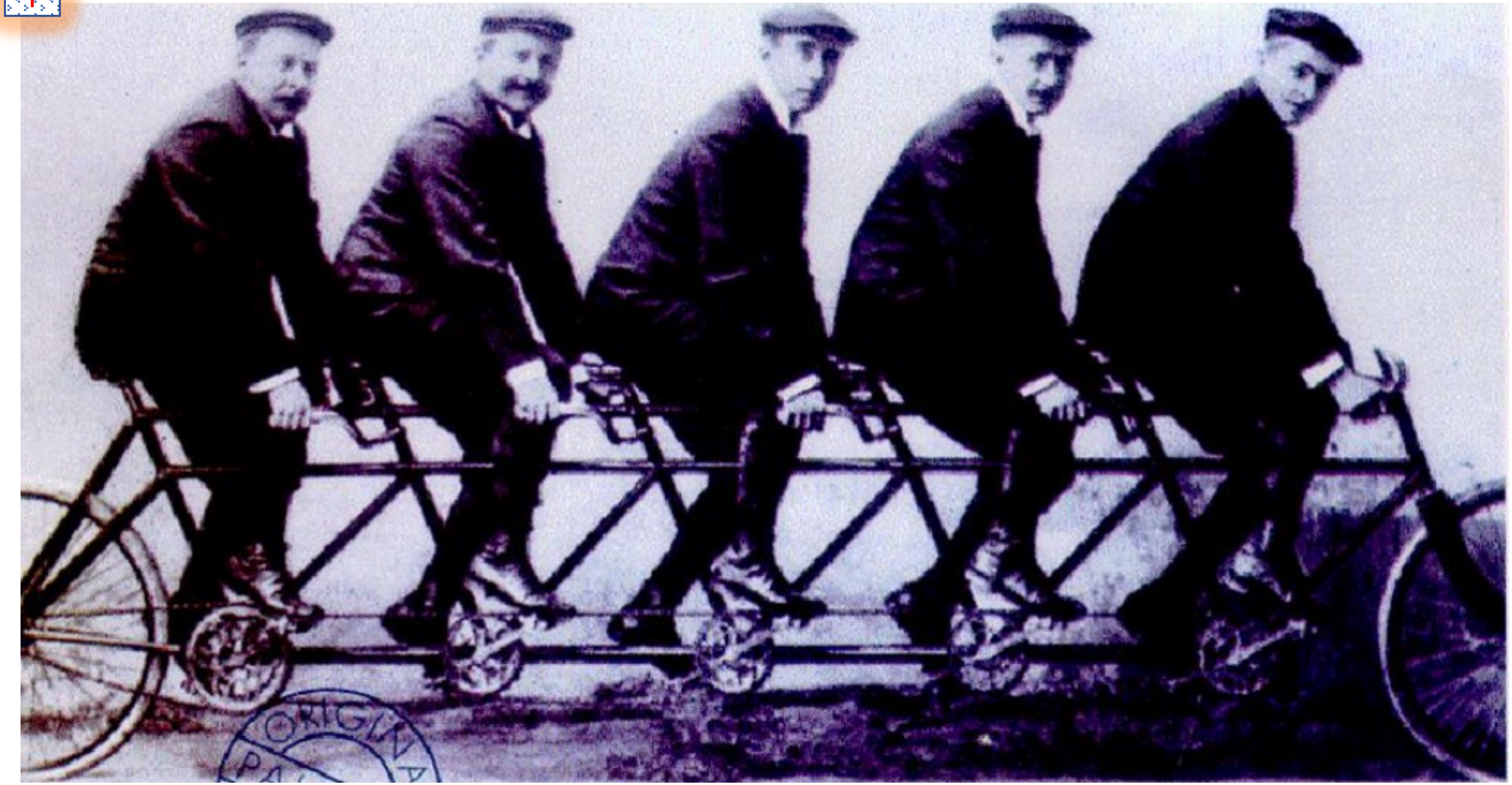
Not Easy: Plasma Accelerator Builder`s Challenge

- Match into/out of plasma with **beam size ≈1 μm** (about 1 mm beta function). Adiabatic matching (Whittum, 1989).
- Control **offsets** between the wakefield driver (laser or beam) and the accelerated electron bunch at **1 μm level.**
- Use **short bunches (few fs)** to minimize energy spread.
- Achieve **synchronization stability of few fs** from injected electron bunch to wakefield (energy stability and spread).
- Control the **charge and beam loading** to compensate energy spread (idea Simon van der Meer).
- New ideas (see later) for better quality.
- Develop and demonstrate **user readiness of a 5 GeV plasma accelerated beam**.



PRL 2002, C. E. Clayton, B. E. Blue, E. S. Dodd, C. Joshi, K. A. Marsh, W. B. Mori, and S. Wang, P. Catravas, S. Chattopadhyay, E. Esarey, and W. P. Leemans, R. Assmann, F. J. Decker, M. J. Hogan, R. Iverson, P. Raimondi, R. H. Siemann, and D. Walz, T. Katsouleas, S. Lee, and P. Muggli

For Example: FEL Requirement



Adapted from P. Schmüser

FEL
=
The Power
of
Coherence

FEL Needs High Quality Beam

Plasma accelerators have small dimensions and they have/should have small dimensions beams! FEL parameters that are being considered (example):

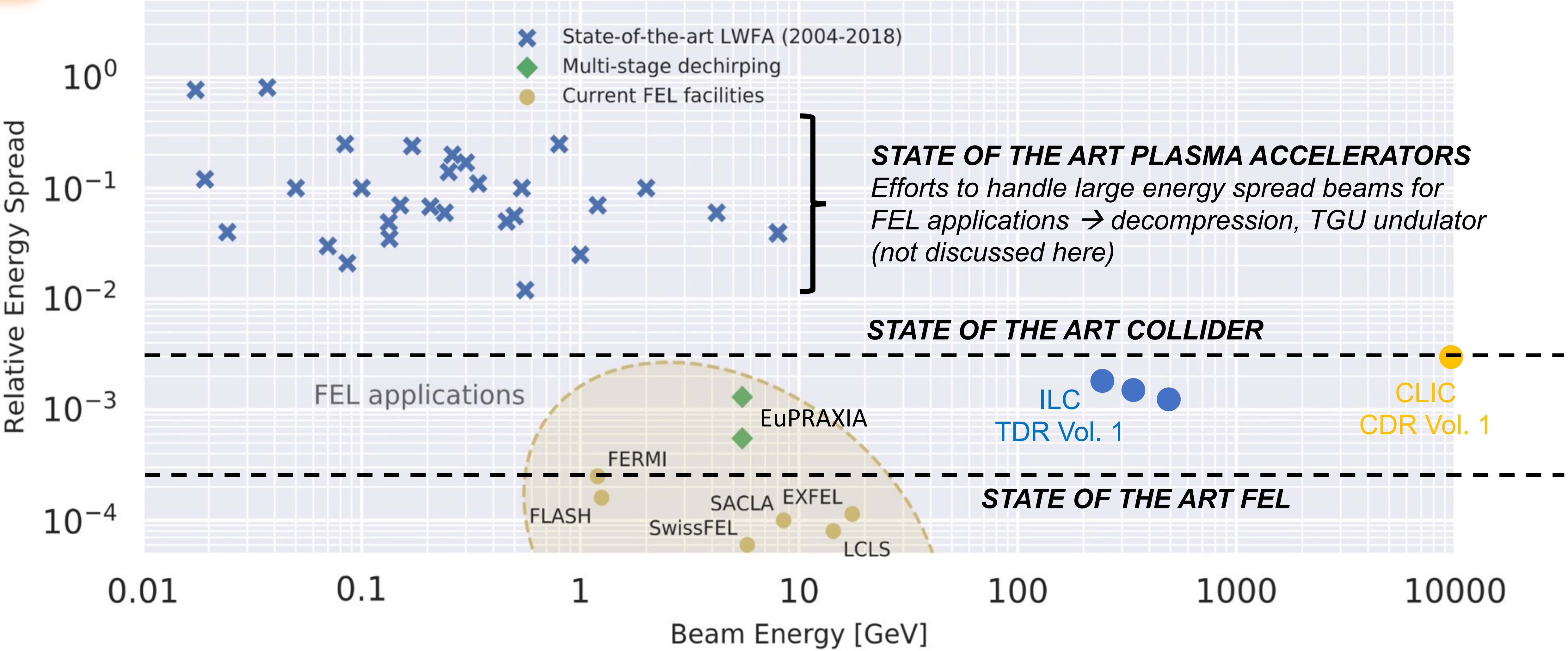
λ = 4 nm, K = 1, λ_u = 15mm, slice energy spread 0.025%, E about 1 GeV

Possible beam parameter sets have been worked out. For example:

Energy:	1 – 5 GeV	
Charge:	10 – 30 pC	
Bunch length rms:	1 μm	(about 3 fs)
Peak current:	2 – 3 kA	
Norm. emittance:	0.2 μm	
Energy spread:	**0.2 %**	(whole bunch)

Equal Energy inside Beam → Small Energy Spread

State of the art in plasma accelerators versus requirements



STATE OF THE ART PLASMA ACCELERATORS

Efforts to handle large energy spread beams for FEL applications → decompression, TGU undulator (not discussed here)

STATE OF THE ART COLLIDER

STATE OF THE ART FEL

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- **Towards Particle Physics**
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Towards a Plasma Collider

DER SPIEGEL

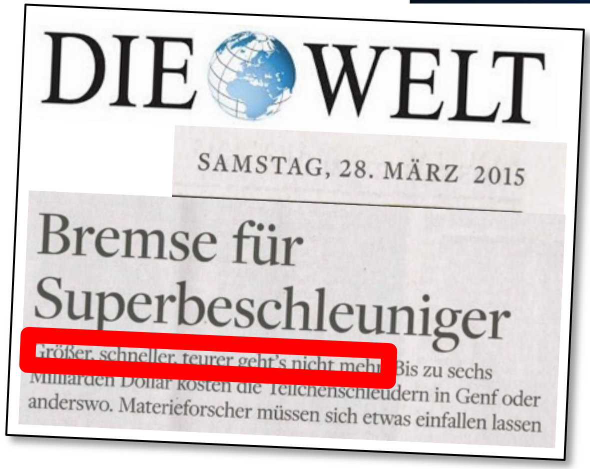
DER SPIEGEL 11/2015

Im Bann von Waxahachie

Physik Forscher bauen immer gewaltigere Teilchenbeschleuniger, um die Geheimnisse des Universums zu enträtseln. Geht es auch eine Nummer kleiner?

Unter den Feldern von Texas erstreckt sich ein verlassener Tunnel, knapp 23 Kilometer lang. Die Zugänge sind verschüttet, in der Röhre sammelt sich Wasser.

Die Ruine nahe dem Städtchen Waxahachie steht für das Trauma der Teilchenphysik: Hier baute die stolze Zunft einst



DIE WELT

SAMSTAG, 28. MÄRZ 2015

Bremse für Superbeschleuniger

Größer, schneller, teurer geht's nicht mehr. Bis zu sechs Milliarden Dollar kosten die Teilchenschleudern in Genf oder anderswo. Materieforscher müssen sich etwas einfallen lassen

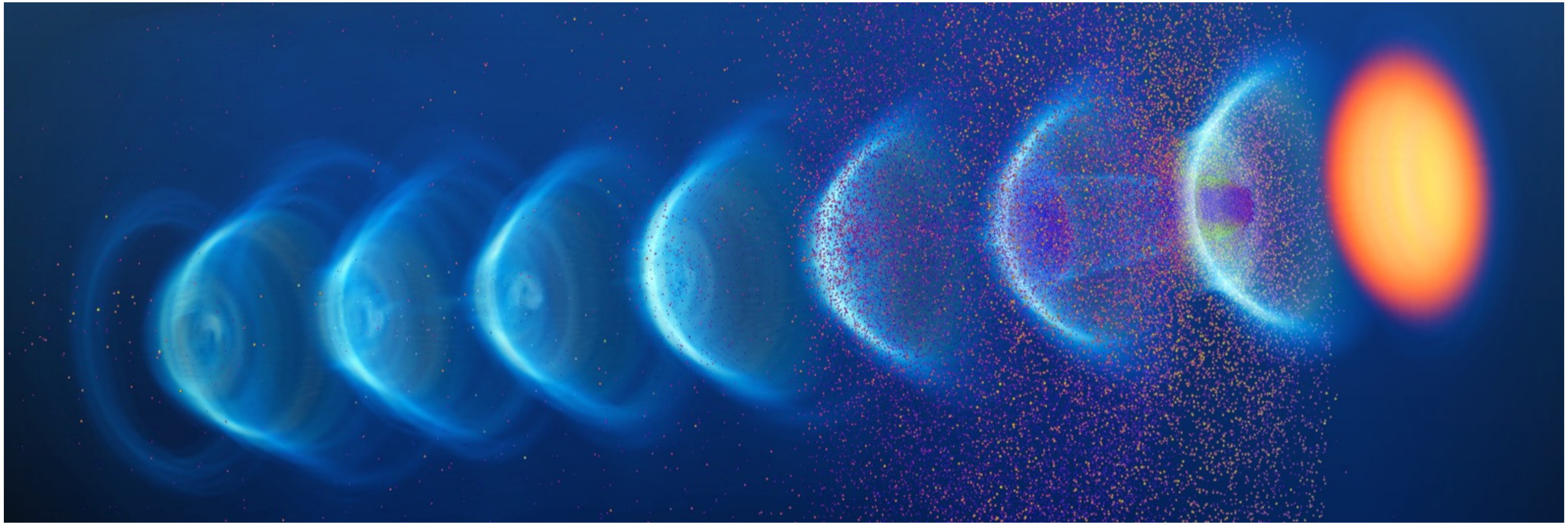


Illustration from PhD A. Ferran Pousa

A 1 TeV collider in 10-100 meters?

Not so easy...

European Strategy for Particle Physics

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

- The European Strategy for Particle Physics is updated every 5 years in a procedure based on wide community input.
- Many of us provided input to this process:
    - Written statements from European Network for Novel Accelerators (EuroNNAc), AWAKE, ALEGRO and EuPRAXIA.
    - Several talks at meetings.
- Strategy defines future directions and priorities for particle physics in Europe and for CERN. Last update: 2020.
- Outcome a great success for advanced accelerators:
    - Importance of accelerator R&D in general.
    - Explicit mentioning of plasma and laser high gradient acceleration.
    - Request for accelerator R&D roadmap, adequate resources, priorities, deliverables for next decade, synergy with other science fields, …

European Strategy for Particle Physics


2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS
by the European Strategy Group
European Strategy Update

3

High-priority future initiatives

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

European Expert Panel Plasma & Laser Acc.

Horizon 2020

Defining a European Particle Physics Roadmap for High-Gradient Novel Accelerators

Expert Panel – Panel chairs:

Chair: Ralph Assmann (DESY/INFN)
Deputy Chair: Edda Gschwendtner (CERN)

Panel members:

Kevin Cassou (IN2P3/IJCLab), Sebastien Corde (IP Paris), Laura Corner (Liverpool), Brigitte Cros (CNRS UPSay), Massimo Ferarrio (INFN), Simon Hooker (Oxford), Rasmus Ischebeck (PSI), Andrea Latina (CERN), Olle Lundh (Lund), Patric Muggli (MPI Munich), Phi Nghiem (CEA/IRFU), Jens Osterhoff (DESY), Tor Raubenheimer (SLAC), Arnd Specka (IN2PR/LLR), Jorge Vieira (IST), Matthew Wing (UCL).

Panel associated members:

Cameron Geddes (LBNL), Mark Hogan (SLAC), Wei Lu (Tsinghua U.) , Pietro Musumeci (UCLA)

Jan 2021 – Feb 2022

Final report: ArXiv & CERN Yellow Report

CERN Yellow Reports: Monographs, CERN-2021-XXX

4 High-gradient Plasma and Laser Accelerators

Editors: R. Assmann[a,b], E. Gschwendtner[c], R. Ischebeck[d]

Panel members: R. Assmann[a,b,] (Chair), E. Gschwendtner[c] (Co-Chair), K. Cassou[e], S. Corde[f], L. Corner[g], B. Cros[h], M. Ferrario[b], S. Hooker[i], R. Ischebeck[d], A. Latina[c], O. Lundh[j], P. Muggli[k], P. Nghiem[l], J. Osterhoff[a], T. Raubenheimer[m], A. Specka[n], J. Vieira[o], M. Wing[p]*

Associated members: C. Geddes[q], M. Hogan[m], W. Lu[r], P. Musumeci[s]

[a]DESY, Hamburg, Germany
[b]LNF/INFN, Frascati, Italy
[c]CERN, Geneva, Switzerland
[d]PSI, Villigen, Switzerland
[e]IJCLab, Orsay, France
[f]IP Paris, Palaiseau, France
[g]Liverpool University, UK
[h]LPGP-CNRS-Université Paris Saclay, Orsay, France
[i]Oxford University, UK
[j]Lund University, Sweden
[k]MPI Physics, Munich, Germany
[l]CEA, Saclay, France
[m]SLAC and Stanford University, California, USA
[n]LLR, Palaiseau, France
[o]IST, Lisbon, Portugal
[p]UCL, London, United Kingdom
[q]LBNL, Berkeley, California, USA
[r]Tsinghua University, Beijing, China
[s]UCLA, Los Angeles, California, USA

4.1 Executive Summary

Novel accelerators have demonstrated acceleration of electrons and positrons with very high accelerating gradients of 1 to >100 GeV/m. This is about 10 to 1000 times higher than achieved in RF accelerators, and as such they have the potential to overcome their limitations. They have produced multi-GeV bunches with single parameters approaching those suitable for a linear collider. A significant reduction in size and, perhaps, cost of future accelerators can therefore in principle be envisaged.

Based on the various R&D achievements, the field has reached the stage of setting up first user facilities for photon and material science in the European research landscape. The many national and regional activities will continue through the end of the 2020s with a strong R&D and construction program, aiming at low energy research infrastructures, for example to drive a free electron laser (FEL) or ultrafast electron diffraction (UED). Various important milestones have been and will be achieved in internationally leading programs at CERN, CLARA, CNRS, DESY, various centres and institutes in

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This contribution should be cited as: High-gradient Plasma and Laser Accelerators, DOI: 10.23731/CYRM-2021-XXX.83, in: European Strategy for Particle Physics - Accelerator R&D Roadmap, Ed. N. Mounet,
CERN Yellow Reports: Monographs, CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 83.

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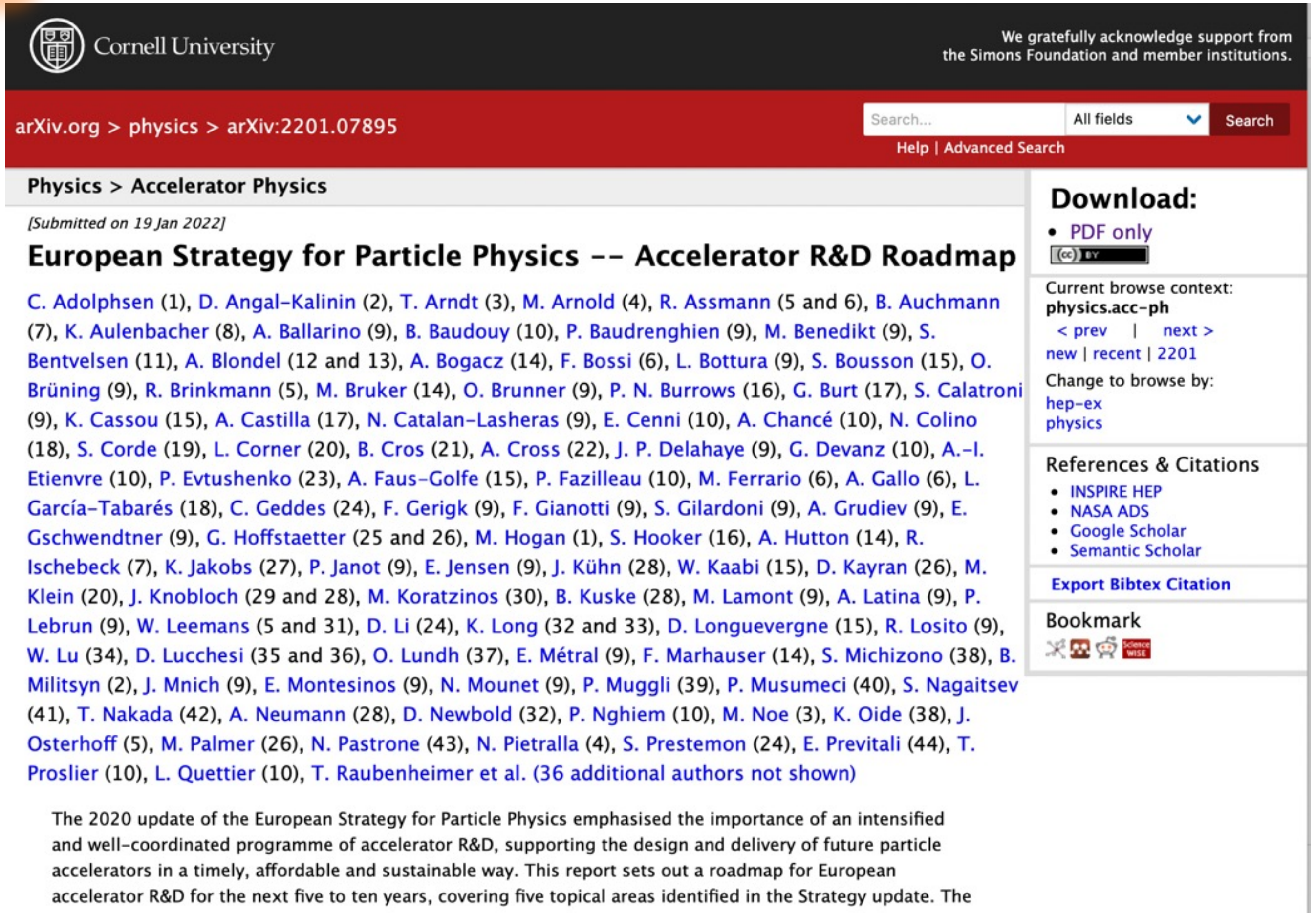
European Expert Panel Plasma & Laser Acc.

Horizon 2020

Report on European Accelerator R&D: Includes detailed discussion on plasma and laser accelerators



Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

arXiv.org > physics > arXiv:2201.07895

Physics > Accelerator Physics

[Submitted on 19 Jan 2022]

European Strategy for Particle Physics -- Accelerator R&D Roadmap

C. Adolphsen (1), D. Angal-Kalinin (2), T. Arndt (3), M. Arnold (4), R. Assmann (5 and 6), B. Auchmann (7), K. Aulenbacher (8), A. Ballarino (9), B. Baudouy (10), P. Baudrenghien (9), M. Benedikt (9), S. Bentvelsen (11), A. Blondel (12 and 13), A. Bogacz (14), F. Bossi (6), L. Bottura (9), S. Bousson (15), O. Brüning (9), R. Brinkmann (5), M. Bruker (14), O. Brunner (9), P. N. Burrows (16), G. Burt (17), S. Calatroni (9), K. Cassou (15), A. Castilla (17), N. Catalan-Lasheras (9), E. Cenni (10), A. Chancé (10), N. Colino (18), S. Corde (19), L. Corner (20), B. Cros (21), A. Cross (22), J. P. Delahaye (9), G. Devanz (10), A.-I. Etienvre (10), P. Evtushenko (23), A. Faus-Golfe (15), P. Fazilleau (10), M. Ferrario (6), A. Gallo (6), L. García-Tabarés (18), C. Geddes (24), F. Gerigk (9), F. Gianotti (9), S. Gilardoni (9), A. Grudiev (9), E. Gschwendtner (9), G. Hoffstaetter (25 and 26), M. Hogan (1), S. Hooker (16), A. Hutton (14), R. Ischebeck (7), K. Jakobs (27), P. Janot (9), E. Jensen (9), J. Kühn (28), W. Kaabi (15), D. Kayran (26), M. Klein (20), J. Knobloch (29 and 28), M. Koratzinos (30), B. Kuske (28), M. Lamont (9), A. Latina (9), P. Lebrun (9), W. Leemans (5 and 31), D. Li (24), K. Long (32 and 33), D. Longuevergne (15), R. Losito (9), W. Lu (34), D. Lucchesi (35 and 36), O. Lundh (37), E. Métral (9), F. Marhauser (14), S. Michizono (38), B. Militsyn (2), J. Mnich (9), E. Montesinos (9), N. Mounet (9), P. Muggli (39), P. Musumeci (40), S. Nagaitsev (41), T. Nakada (42), A. Neumann (28), D. Newbold (32), P. Nghiem (10), M. Noe (3), K. Oide (38), J. Osterhoff (5), M. Palmer (26), N. Pastrone (43), N. Pietralla (4), S. Prestemon (24), E. Previtali (44), T. Proslier (10), L. Quettier (10), T. Raubenheimer et al. (36 additional authors not shown)

The 2020 update of the European Strategy for Particle Physics emphasised the importance of an intensified and well-coordinated programme of accelerator R&D, supporting the design and delivery of future particle accelerators in a timely, affordable and sustainable way. This report sets out a roadmap for European accelerator R&D for the next five to ten years, covering five topical areas identified in the Strategy update. The

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http://arxiv.org/abs/2201.07895

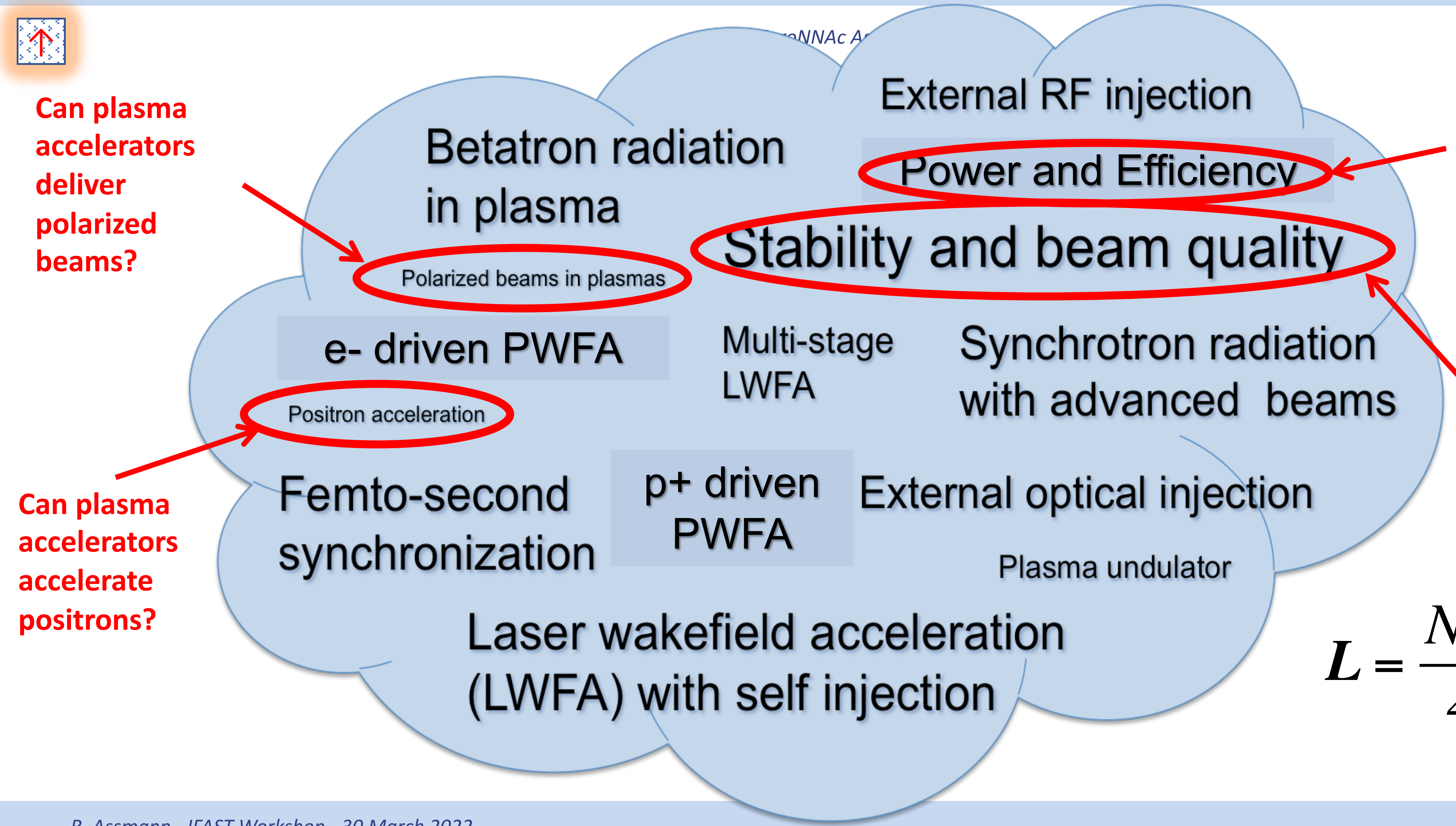
EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

European Strategy Update

LDG Laboratory Directors Group

R&D Paths Plasma Accelerators



Can plasma accelerators deliver polarized beams?

Can plasma accelerators accelerate positrons?

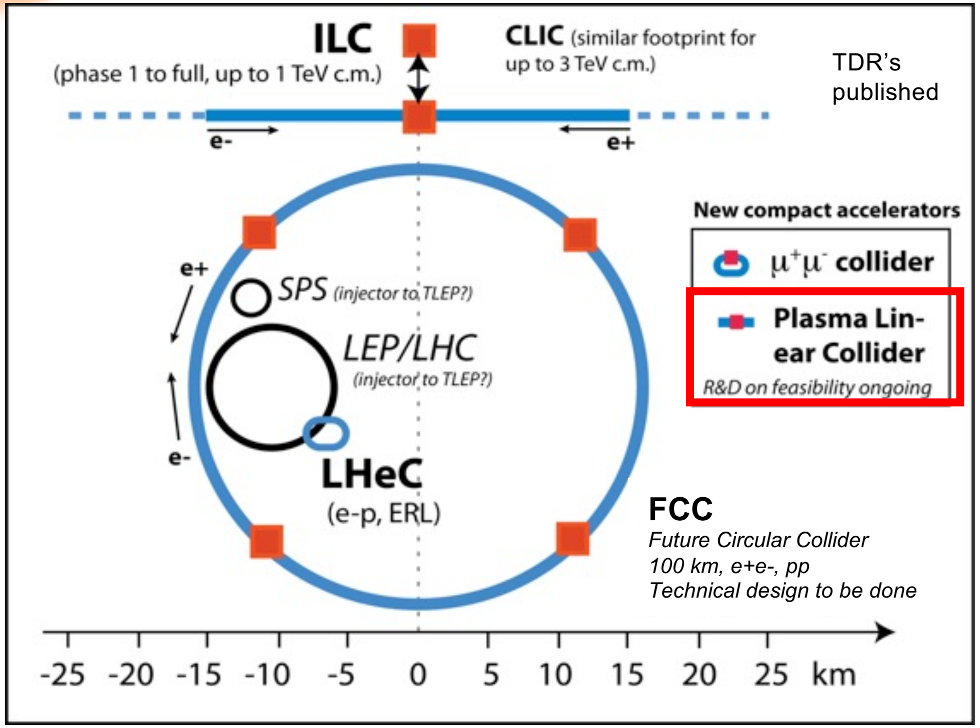
Can plasma accelerators deliver integrated luminosity?

Can plasma accelerators deliver peak luminosity?

$$L = \frac{N_{e+} N_{e-} f_r}{4\pi\sigma_x\sigma_y}$$

Can we shrink the Linear Collider?

Provide e- and e+ beams in the TeV energy regime and produce > 10^{34} cm^{-2} s^{-1} luminosity



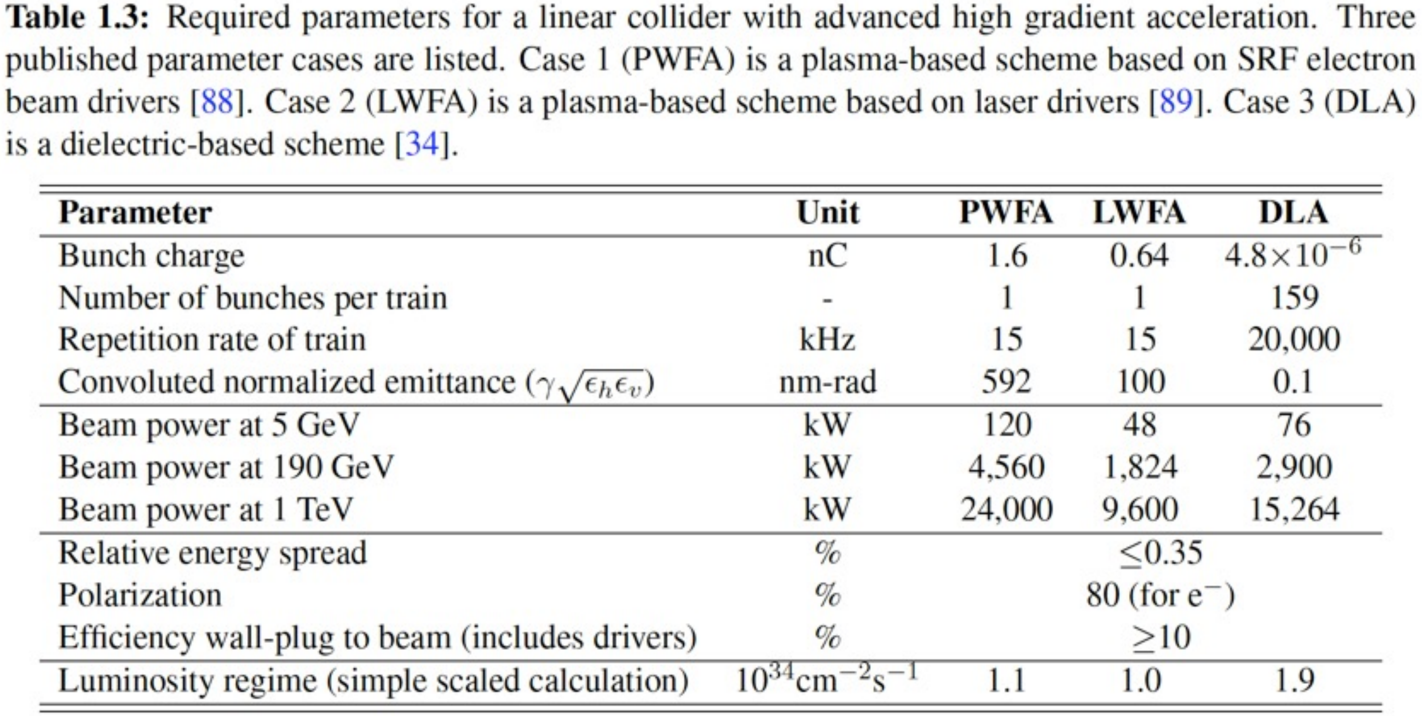


Table 1.3: Required parameters for a linear collider with advanced high gradient acceleration. Three published parameter cases are listed. Case 1 (PWFA) is a plasma-based scheme based on SRF electron beam drivers [88]. Case 2 (LWFA) is a plasma-based scheme based on laser drivers [89]. Case 3 (DLA) is a dielectric-based scheme [34].

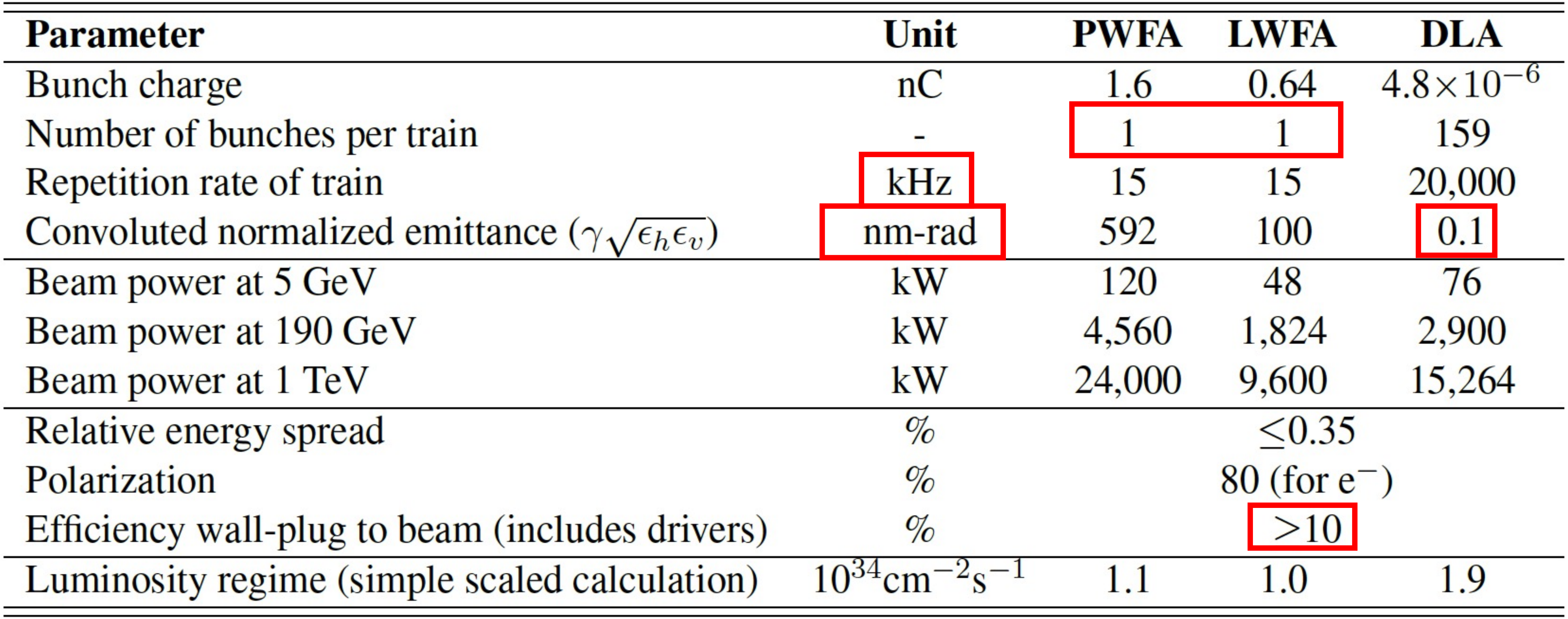
Parameter	Unit	PWFA	LWFA	DLA
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20,000
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm-rad	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 GeV	kW	4,560	1,824	2,900
Beam power at 1 TeV	kW	24,000	9,600	15,264
Relative energy spread	%		$\leq$0.35	
Polarization	%		80 (for e^-)	
Efficiency wall-plug to beam (includes drivers)	%		$\geq$10	
Luminosity regime (simple scaled calculation)	10^{34}cm^{-2}s^{-1}	1.1	1.0	1.9

from expert panel report

- **No fundamental show-stopper but a lot of R&D still required.**
- There can be very interesting and useful interim steps (non-linear QED, fixed target, dark matter, …)
- **Devil is in the details!** Answer requires detailed simulation, calculations, R&D, designs and tests!
- How and when can we arrive at readiness for for high energy particle physics, e.g. a TeV collider?

Can we shrink the Linear Collider?

Provide e- and e+ beams in the TeV energy regime and produce > 10^{34} cm^{-2} s^{-1} luminosity



Parameter	**Unit**	**PWFA**	**LWFA**	**DLA**
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
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Beam power at 190 GeV	kW	4,560	1,824	2,900
Beam power at 1 TeV	kW	24,000	9,600	15,264
Relative energy spread	%	$\leq$0.35		
Polarization	%	80 (for e^-)		
Efficiency wall-plug to beam (includes drivers)	%	>10		
Luminosity regime (simple scaled calculation)	$10^{34}cm^{-2}s^{-1}$	1.1	1.0	1.9

from expert panel report

Possible Beam Parameters for High Energies

Situation TODAY:

- Electron beam acceleration in a single stage works with reasonably good quality (typically **1-5 GeV HQ energy gain, record 8/30 GeV**)
- Electron charge in HQ beam at **10 – 50 pC** (record **500 pC** beam, few 100 nC with 100% energy spread). No theoretical solution for 1 nC HQ electron beam yet.
- Start to end for **2 electron stages up to 5 GeV and factor 3 reduction** of length.
- Positrons: **first acceleration of a few positrons** – no theroretical solution for a positron plasma linac yet.
- Presently **power efficiency low** and power consumption high.
- Use case of plasma / dielectric accelerators:
    - Compact plasma based FEL
    - Low power HEP studies with electron beams (e.g. detector tests)
    - Compact or special inexpensive setup cases (standard RF does not fit facility or budget)

High Energy Study Case (175 – 190 GeV)

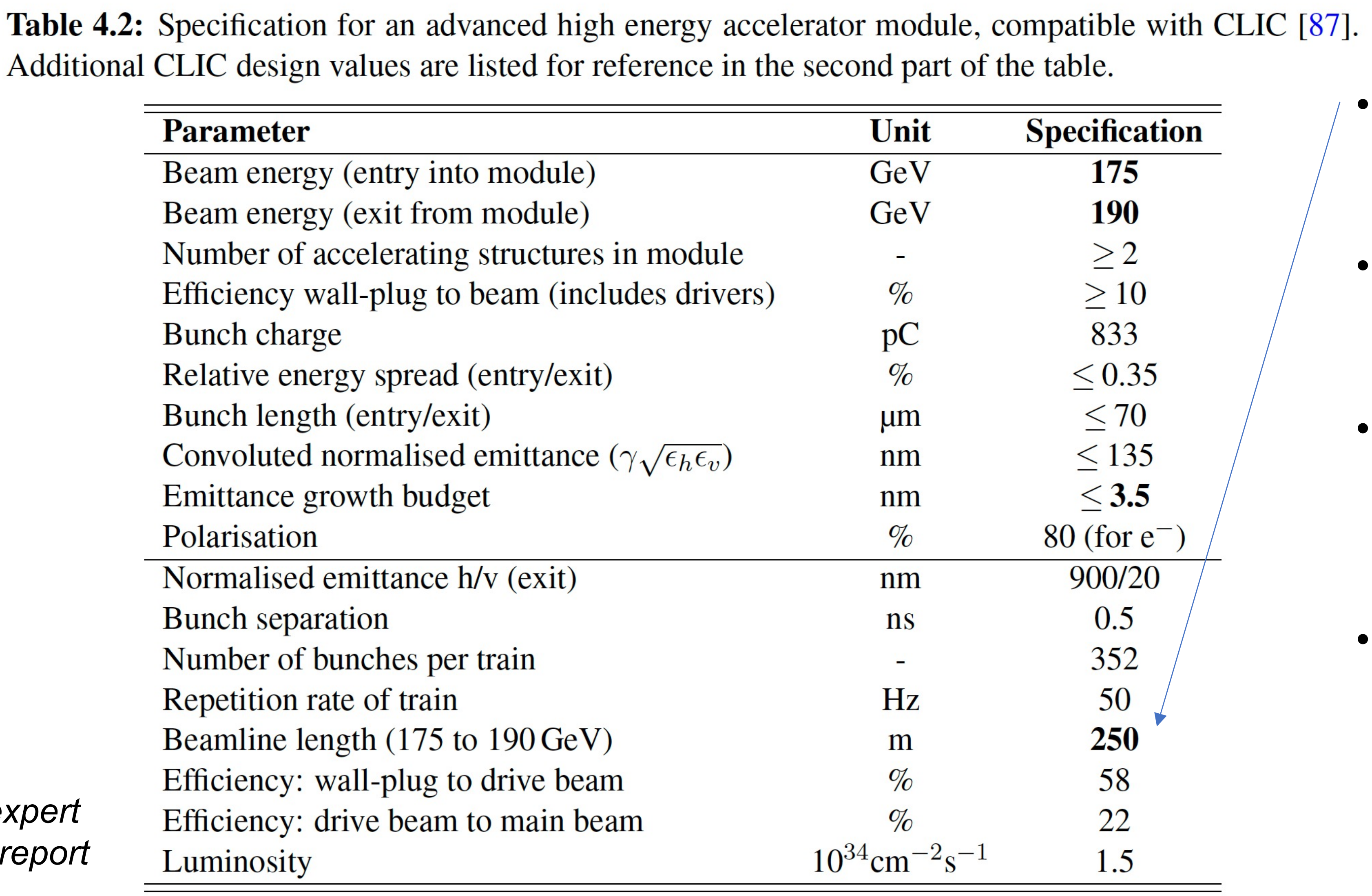


Table 4.2: Specification for an advanced high energy accelerator module, compatible with CLIC [87]. Additional CLIC design values are listed for reference in the second part of the table.

Parameter	Unit	Specification
Beam energy (entry into module)	GeV	**175**
Beam energy (exit from module)	GeV	**190**
Number of accelerating structures in module	-	≥ 2
Efficiency wall-plug to beam (includes drivers)	%	≥ 10
Bunch charge	pC	833
Relative energy spread (entry/exit)	%	≤ 0.35
Bunch length (entry/exit)	µm	≤ 70
Convoluted normalised emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm	≤ 135
Emittance growth budget	nm	$\leq$ **3.5**
Polarisation	%	80 (for e$^-$)
Normalised emittance h/v (exit)	nm	900/20
Bunch separation	ns	0.5
Number of bunches per train	-	352
Repetition rate of train	Hz	50
Beamline length (175 to 190 GeV)	m	**250**
Efficiency: wall-plug to drive beam	%	58
Efficiency: drive beam to main beam	%	22
Luminosity	10^{34}cm^{-2}s^{-1}	1.5

from expert panel report

- Size of a 15 GeV advanced accelerator multi-stage unit for e-?
- Should be significantly shorter (less expensive) than 250 m CLIC solution.
- Must include in/out-coupling of driver, focusing, stage coupling, diagnostics, correctors, …
- No detailed design & calculation for advanced accelerators. Pre-condition for claiming benefits.

Low Energy Particle Physics Cases Specified

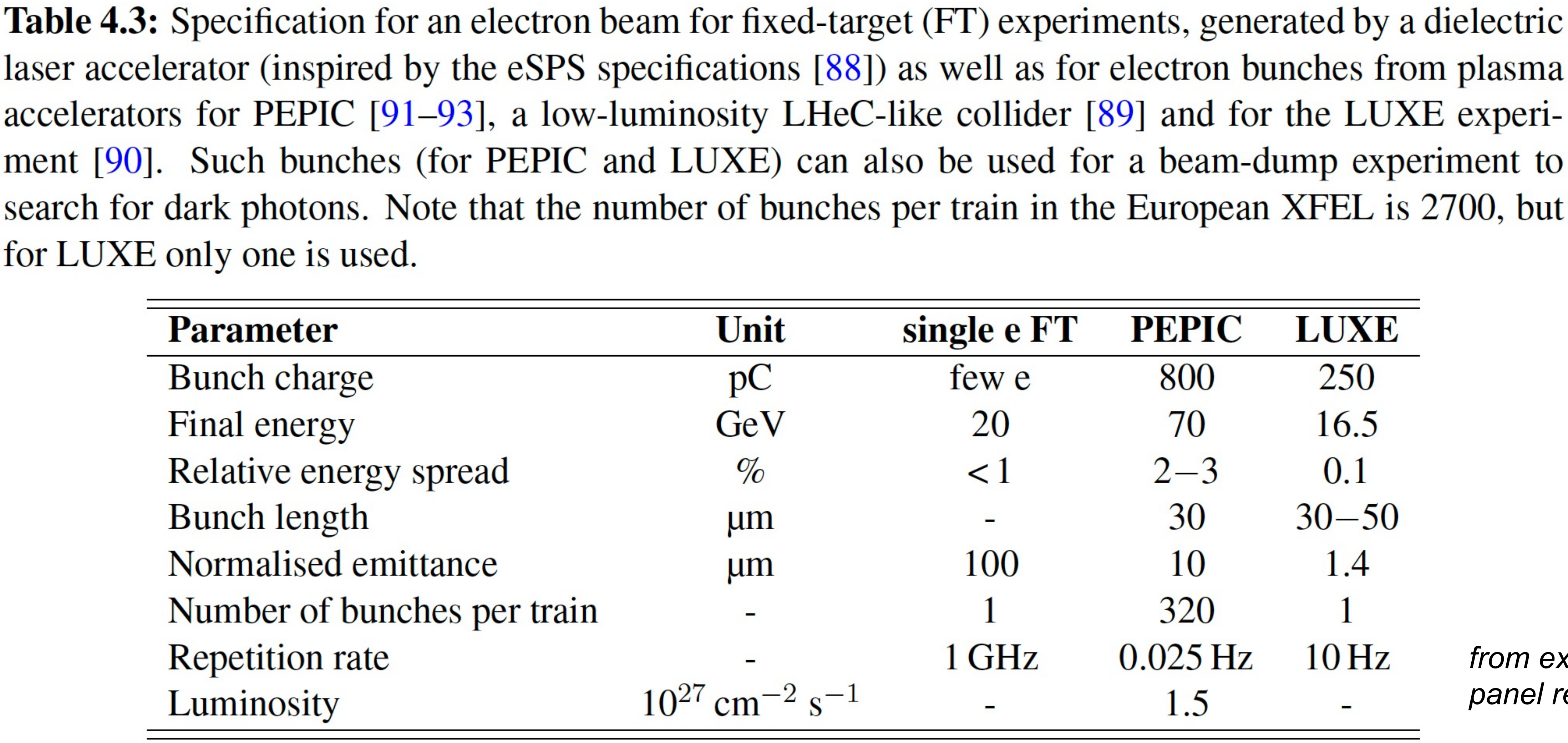
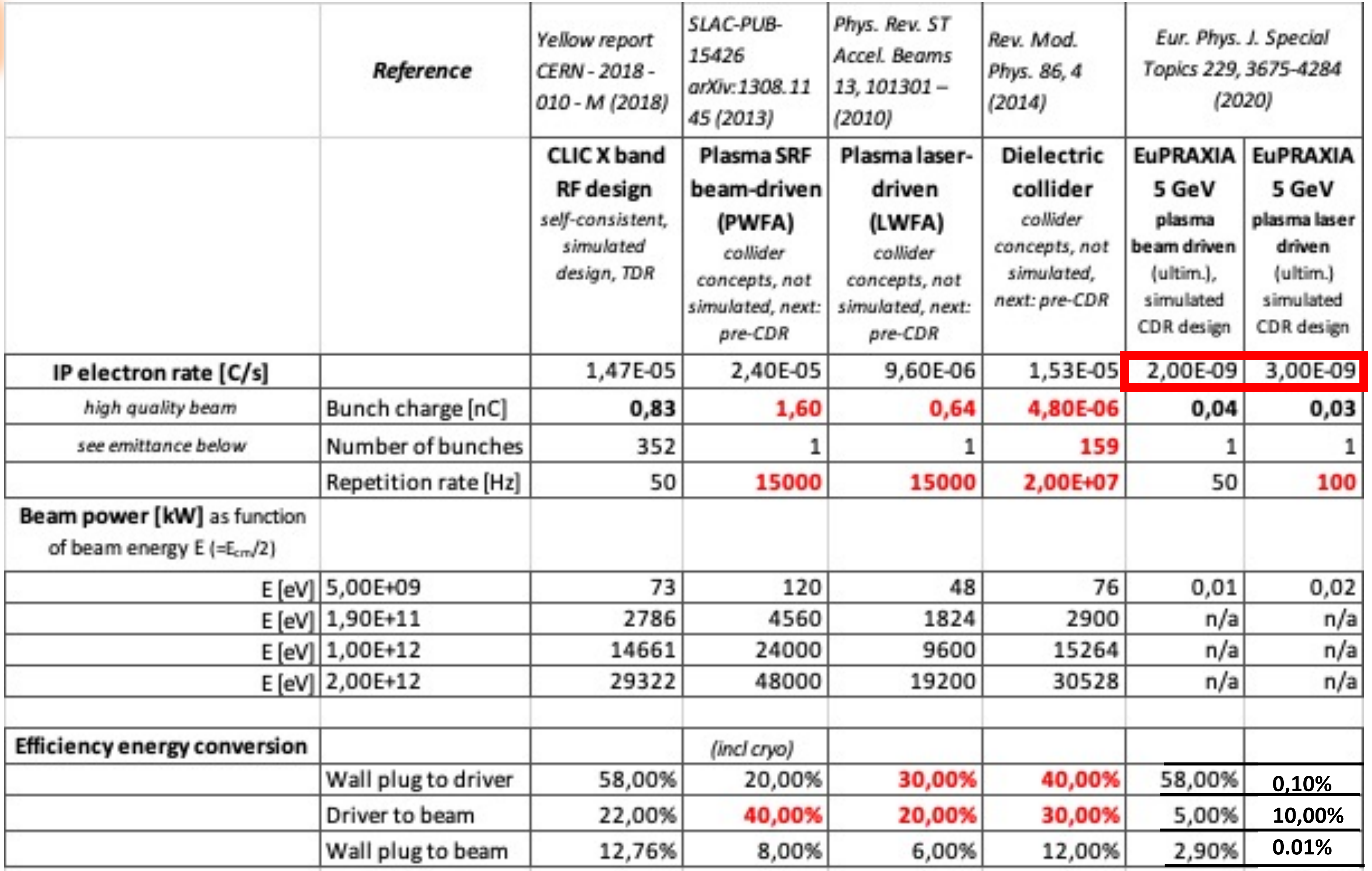


Table 4.3: Specification for an electron beam for fixed-target (FT) experiments, generated by a dielectric laser accelerator (inspired by the eSPS specifications [88]) as well as for electron bunches from plasma accelerators for PEPIC [91–93], a low-luminosity LHeC-like collider [89] and for the LUXE experiment [90]. Such bunches (for PEPIC and LUXE) can also be used for a beam-dump experiment to search for dark photons. Note that the number of bunches per train in the European XFEL is 2700, but for LUXE only one is used.

Parameter	**Unit**	**single e FT**	**PEPIC**	**LUXE**
Bunch charge	pC	few e	800	250
Final energy	GeV	20	70	16.5
Relative energy spread	%	<1	2–3	0.1
Bunch length	µm	-	30	30–50
Normalised emittance	µm	100	10	1.4
Number of bunches per train	-	1	320	1
Repetition rate	-	1 GHz	0.025 Hz	10 Hz
Luminosity	$10^{27}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	-	1.5	-

from expert panel report

Possible Beam Parameters Spreadsheet I



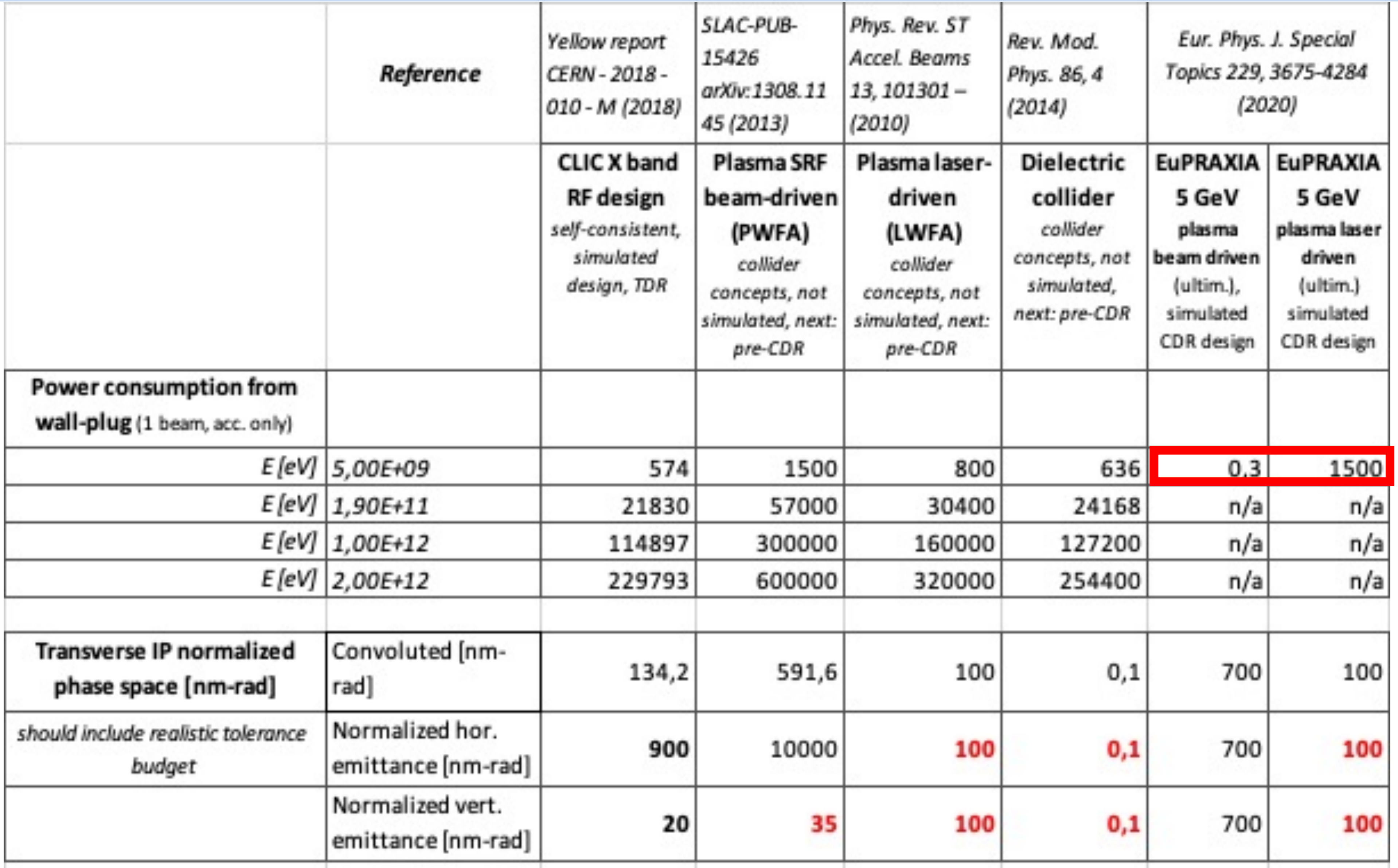
	Reference	*Yellow report CERN - 2018 - 010 - M (2018)*	*SLAC-PUB-15426 arXiv:1308.1145 (2013)*	*Phys. Rev. ST Accel. Beams 13, 101301 – (2010)*	*Rev. Mod. Phys. 86, 4 (2014)*	*Eur. Phys. J. Special Topics 229, 3675-4284 (2020)*	
		CLIC X band RF design *self-consistent, simulated design, TDR*	**Plasma SRF beam-driven (PWFA)** *collider concepts, not simulated, next: pre-CDR*	**Plasma laser-driven (LWFA)** *collider concepts, not simulated, next: pre-CDR*	**Dielectric collider** *collider concepts, not simulated, next: pre-CDR*	**EuPRAXIA 5 GeV plasma beam driven** (ultim.), simulated CDR design	**EuPRAXIA 5 GeV plasma laser driven** (ultim.) simulated CDR design
IP electron rate [C/s]		1,47E-05	2,40E-05	9,60E-06	1,53E-05	2,00E-09	3,00E-09
high quality beam	Bunch charge [nC]	**0,83**	**1,60**	**0,64**	**4,80E-06**	**0,04**	**0,03**
see emittance below	Number of bunches	352	1	1	**159**	1	1
	Repetition rate [Hz]	50	**15000**	**15000**	**2,00E+07**	50	**100**
Beam power [kW] as function of beam energy E (=E_{cm}/2)							
E [eV]	5,00E+09	73	120	48	76	0,01	0,02
E [eV]	1,90E+11	2786	4560	1824	2900	n/a	n/a
E [eV]	1,00E+12	14661	24000	9600	15264	n/a	n/a
E [eV]	2,00E+12	29322	48000	19200	30528	n/a	n/a
Efficiency energy conversion			*(incl cryo)*				
	Wall plug to driver	58,00%	20,00%	**30,00%**	**40,00%**	58,00%	**0,10%**
	Driver to beam	22,00%	**40,00%**	**20,00%**	**30,00%**	5,00%	**10,00%**
	Wall plug to beam	12,76%	8,00%	6,00%	12,00%	2,90%	**0.01%**

Column 1:	*CLIC reference design*
Columns 2-4:	*Advanced collider sketches*
Column 5-6:	*EuPRAXIA conceptual design*

In next 8 years:

- Up to **3e9 C/s** high quality beam at up to 5 GeV?
- Designed with European laser industry, RF labs
- Tradeoff with quality: can imagine factor 10 more rate with lower quality, not much more

Possible Beam Parameters Spreadsheet II



	Reference	*Yellow report CERN - 2018 - 010 - M (2018)*	*SLAC-PUB-15426 arXiv:1308.1145 (2013)*	*Phys. Rev. ST Accel. Beams 13, 101301 – (2010)*	*Rev. Mod. Phys. 86, 4 (2014)*	*Eur. Phys. J. Special Topics 229, 3675-4284 (2020)*	
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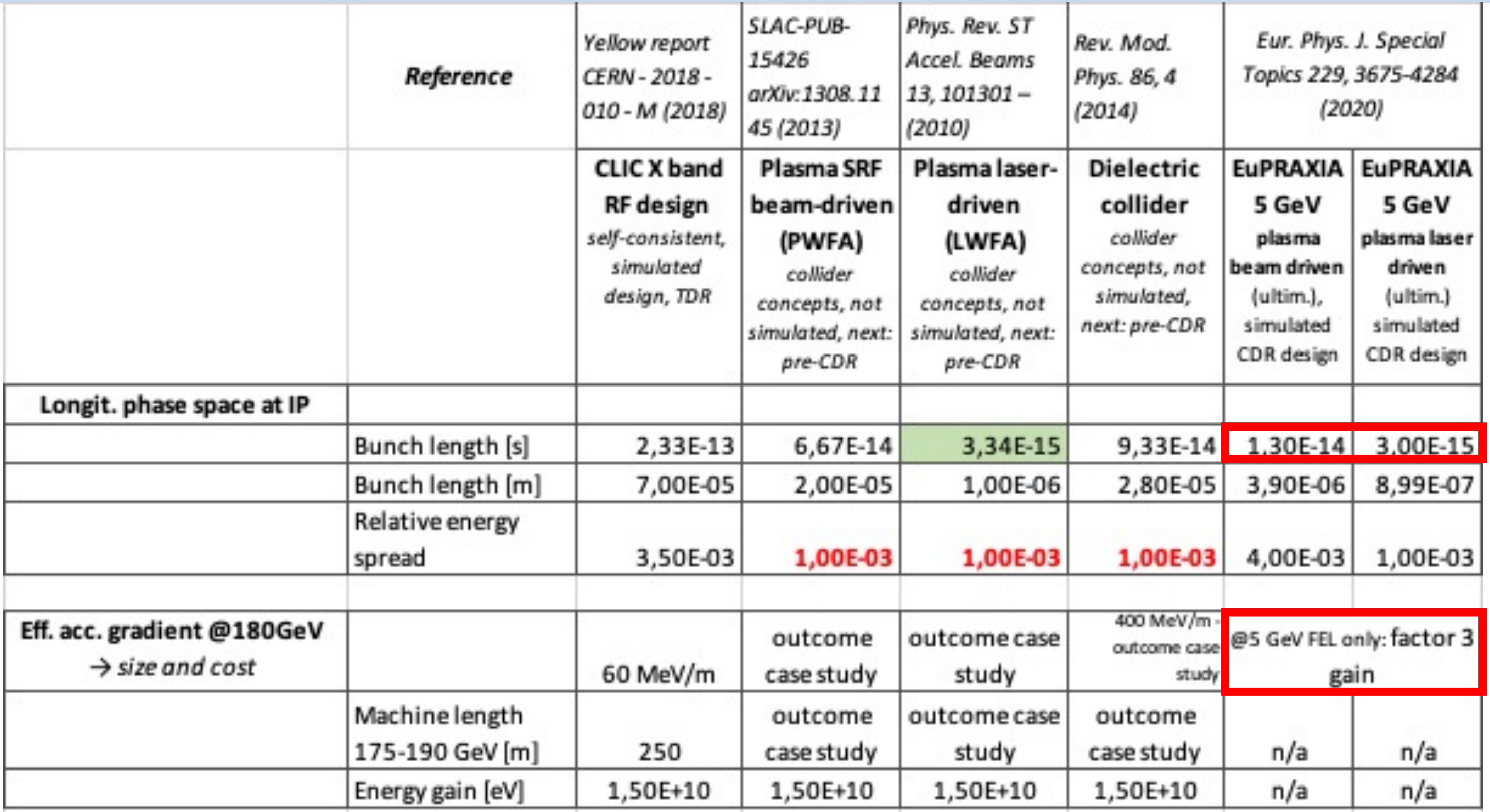
Power consumption from wall-plug (1 beam, acc. only)							
E [eV]	*5,00E+09*	574	1500	800	636	0,3	1500
E [eV]	*1,90E+11*	21830	57000	30400	24168	n/a	n/a
E [eV]	*1,00E+12*	114897	300000	160000	127200	n/a	n/a
E [eV]	*2,00E+12*	229793	600000	320000	254400	n/a	n/a
Transverse IP normalized phase space [nm-rad]	Convoluted [nm-rad]	134,2	591,6	100	0,1	700	100
should include realistic tolerance budget	Normalized hor. emittance [nm-rad]	**900**	10000	**100**	**0,1**	700	**100**
	Normalized vert. emittance [nm-rad]	**20**	**35**	**100**	**0,1**	700	**100**

Possible Beam Parameters Spreadsheet III



	Reference	*Yellow report CERN - 2018 - 010 - M (2018)*	*SLAC-PUB-15426 arXiv:1308.1145 (2013)*	*Phys. Rev. ST Accel. Beams 13, 101301 – (2010)*	*Rev. Mod. Phys. 86, 4 (2014)*	*Eur. Phys. J. Special Topics 229, 3675-4284 (2020)*	
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Longit. phase space at IP							
	Bunch length [s]	2,33E-13	6,67E-14	3,34E-15	9,33E-14	1,30E-14	3,00E-15
	Bunch length [m]	7,00E-05	2,00E-05	1,00E-06	2,80E-05	3,90E-06	8,99E-07
	Relative energy spread	3,50E-03	1,00E-03	1,00E-03	1,00E-03	4,00E-03	1,00E-03
Eff. acc. gradient @180GeV → *size and cost*		60 MeV/m	outcome case study	outcome case study	400 MeV/m - outcome case study	@5 GeV FEL only: factor 3 gain	
	Machine length 175-190 GeV [m]	250	outcome case study	outcome case study	outcome case study	n/a	n/a
	Energy gain [eV]	1,50E+10	1,50E+10	1,50E+10	1,50E+10	n/a	n/a

Realistic Reduction Footprint at 5 GeV

RF Accelerators

> 30,000 operational – many serve for Health

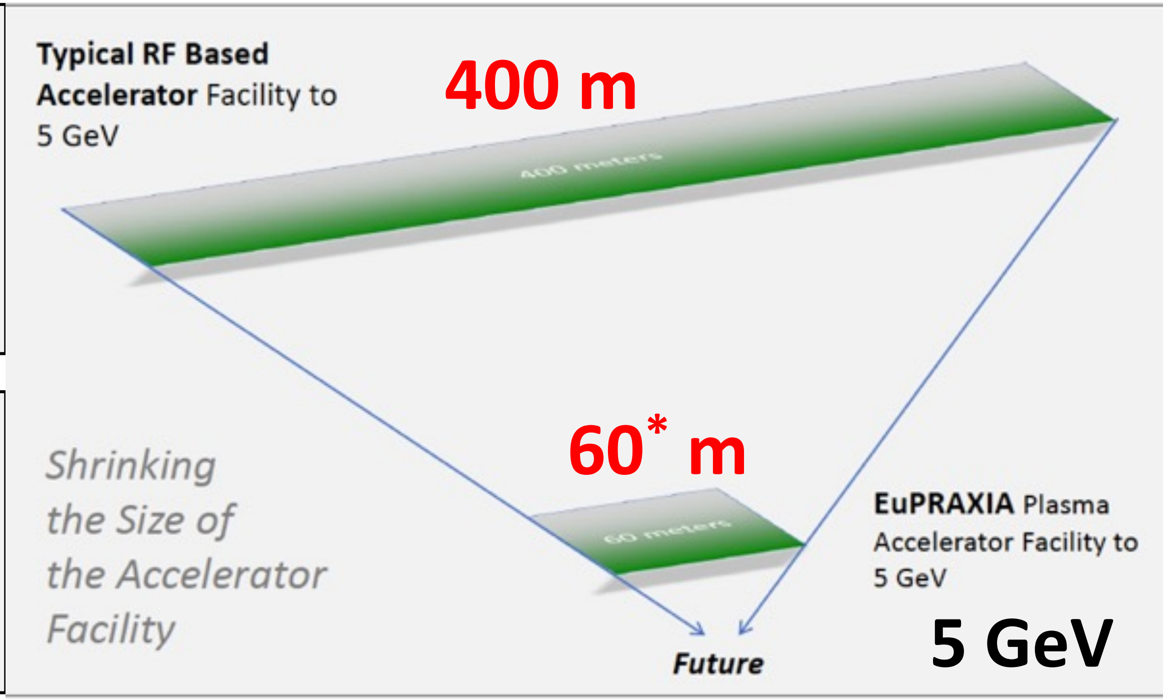
30 million Volt **per meter**

RF: 90 years of success story for society

Plasma Accelerators

first user facility to be realized

100,000 million Volt **per meter**



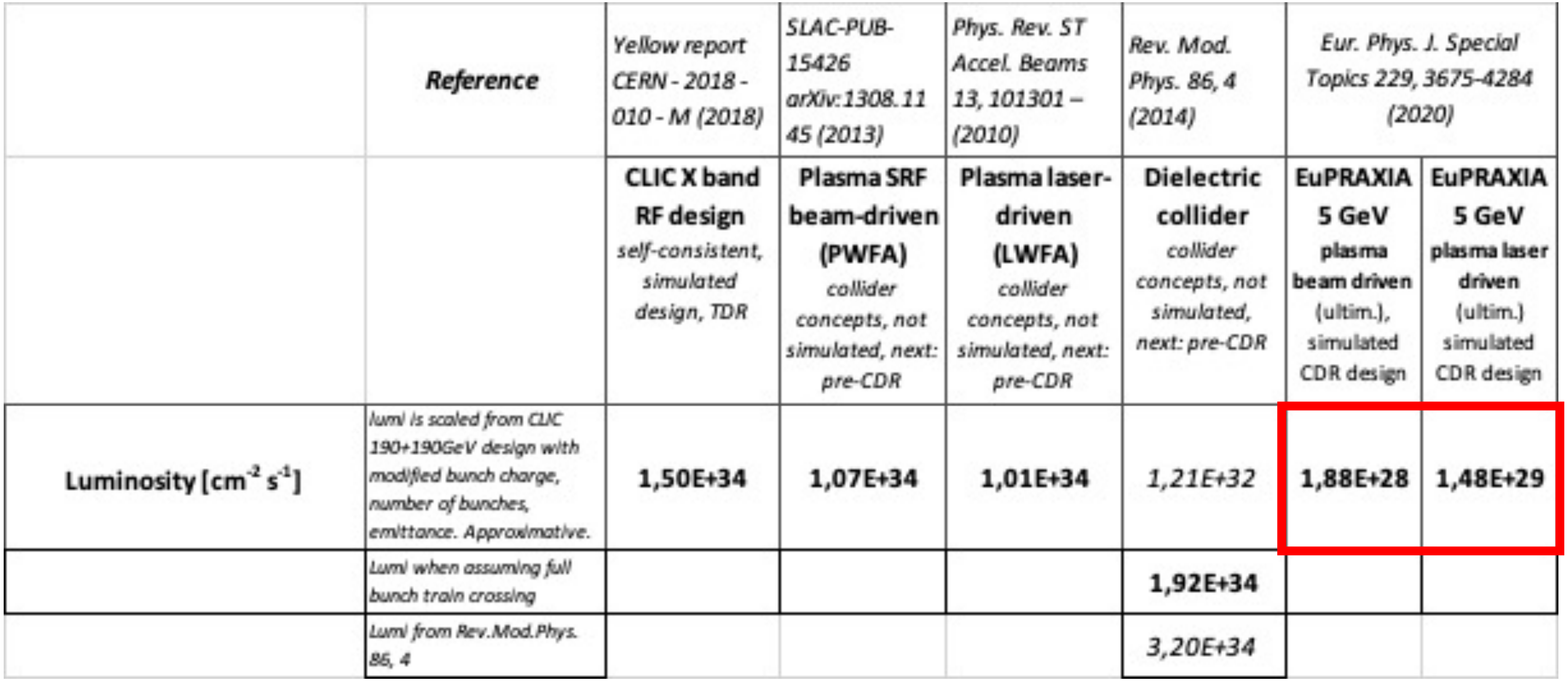
Added value

new Research Infrastructures due to compactness and cost-efficiency

bringing new capabilities to science, institutes, hospitals, universities, industry, developing countries.

[*] *realistic design including all required infrastructure for powering, shielding, …*

Possible Beam Parameters Spreadsheet IV



	Reference	*Yellow report CERN - 2018 - 010 - M (2018)*	*SLAC-PUB-15426 arXiv:1308.1145 (2013)*	*Phys. Rev. ST Accel. Beams 13, 101301 – (2010)*	*Rev. Mod. Phys. 86, 4 (2014)*	*Eur. Phys. J. Special Topics 229, 3675-4284 (2020)*	
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Luminosity $[cm^{-2} s^{-1}]$	*lumi is scaled from CLIC 190+190GeV design with modified bunch charge, number of bunches, emittance. Approximative.*	**1,50E+34**	**1,07E+34**	**1,01E+34**	*1,21E+32*	**1,88E+28**	**1,48E+29**
	Lumi when assuming full bunch train crossing				**1,92E+34**		
	Lumi from Rev.Mod.Phys. 86, 4				*3,20E+34*		

Plasma-accelerated e- beam in EuPRAXIA presently would enable a collider luminosity of 1.5e29, about 5 orders of magnitude below the linear collider goals (ignoring problems on e+, staging). This reresents a major advance and success. Clearly, more R&D is required…

Plasma and Laser Accelerators for HEP I

- Strong and successful international/European projects and their related coordination bodies exist in this area, with multi year programs ahead (“coordination through common multi-lateral projects”):
  - **EuPRAXIA Research Infrastructure on ESFRI roadmap** – building two FEL facilities (one beam / one laser driven plasma user facility) – cost 569 M€ – entering preparatory phase with > 1,550 person-months (funding agencies advisory body formed as part of EuPRAXIA-PPP) – mainly for applied science users but will demonstrate some HEP milestones
  - **AWAKE** collaboration at CERN (AWAKE run 2)
  - **I.FAST plasma WP6** incl. EU-funded **Europ. Network for Novel Accelerators**: loose coordination/EAAC since 2011
  - **ACHIP** collaboration on dielectric accelerators (US and Europe coordinators)
- It is important to **ensure full success of those projects**: highly visible, will achieve major milestones, will demonstrate critical goals relevant for particle physics (steps towards a collider or HEP experiments).
- To establish usefulness for particle physics collider or HEP experiment, expert panel pointed out as **highest priority** (beyond existing projects and technical/national deliverables) a **feasibility study / pre-CDR:**
  - This is not in the scope of above projects. Needs extra funding, coordination and new structure.
  - Conceptual work to be done, for plasmas/dielectrics, theory, simulation plus few demo exp. Includes basic R&D on not solved problems for a collider (e.g. positrons). EuPRAXIA, AWAKE, I.FAST, … cannot perform this work.
  - Therefore **fully support a complementary particle physics based structure** for a resource-loaded feasibility study for a plasma/dielectric collider and/or particle physics experiment.

Plasma and Laser Accelerators for HEP II

- On the longer term (beyond pre-CDR) we have included in our report a possible **particle physics plasma accelerator demonstration facility** for the 2030’s:
  - Design would be part of the feasibility / pre-CDR study mentioned before
  - Expert panel: Too early to propose in detail now (detailed budget, parameters, deliverables, …) but important step for the future if feasibility is shown.
  - Particle physics plasma accelerator demo facility is clearly out of scope for existing projects. One of the European or national projects could develop into the host for this possible facility, if there is sufficient support and interest.
  - Requires the same **complementary particle physics based structure** supported on previous slide.

- **EuPRAXIA`s role**:
  - A number of strong projects are ahead that we must complete successfully, including EuPRAXIA.
  - EuPRAXIA will demonstrate high beam quality, 2 stages, 100 Hz operation, stability, user readiness.
  - EuPRAXIA will build two FEL`s in Europe, one beam-driven and one laser-driven.
  - If it does not work, with all the European excellence connected, a collider will surely also not work.

Outline

Horizon 2020

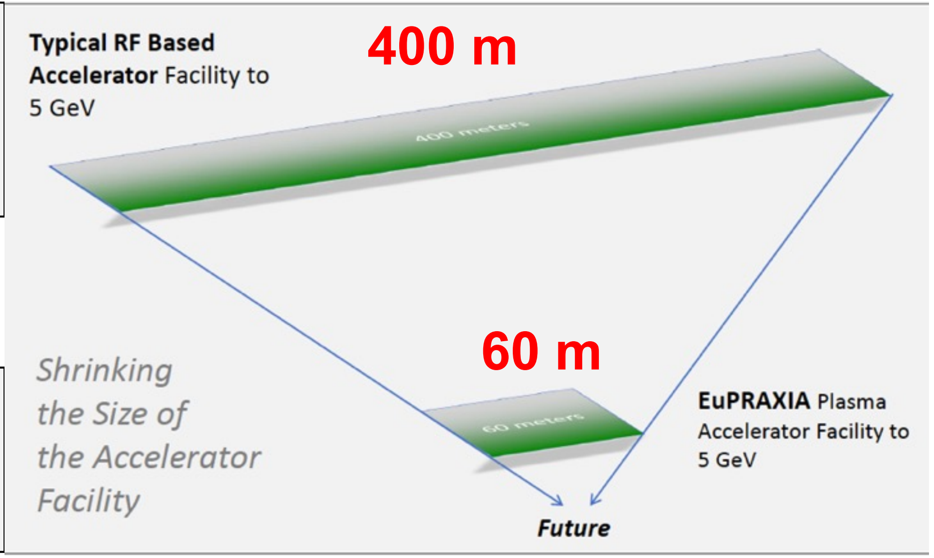
- The Plasma Accelerator Context
- **The EuPRAXIA Objective**
- ESFRI and EuPRAXIA
- EuPRAXIA as a User Facility
- EuPRAXIA Implementation
- EuPRAXIA Innovation
- EuPRAXIA ESFRI Features
- Towards Particle Physics
- Conclusion

European Plasma Research Accelerator with eXcellence In Applications

European High-Tech Project on Accelerator Innovation

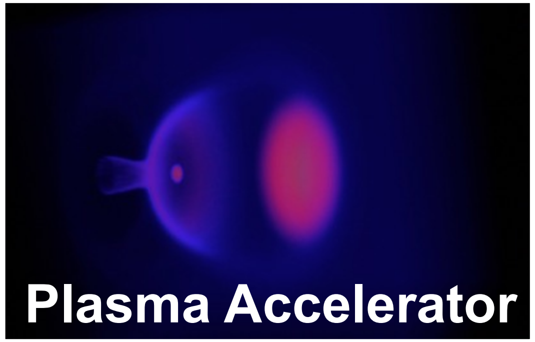
RF Particle Accelerators
> 30,000 operational – many serve for Health
30 million Volt per meter
RF: 90 years of success story for society

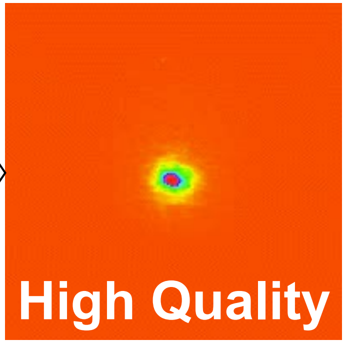
Plasma Particle Accelerators
first user facility to be realized
100 billion Volt per meter



600+ page CDR,
240 scientists
contributed

Added value
new RI's due to compactness and cost-efficiency – ultra-fast science bringing new capabilities to institutes, hospitals, universities, industry, countries.





http://www.eupraxia-project.eu/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

The EuPRAXIA Project

http://www.eupraxia-project.eu/

Horizon 2020

- First ever design of a **plasma accelerator facility**.
- **Conceptual Design Report for a distributed research infrastructure** funded by EU Horizon2020 program. Completed by 16+25 institutes.
- Challenges addressed by EuPRAXIA since 2015:
    - **Can plasma accelerators produce usable electron beams**?
    - **For what can we use those beams** while we increase the beam energy towards HEP and collider usages?
- **Next phase consortium** with 40 partners + 10 observers.
- Preparatory Phase project: **2022 – 2026** (submitted, to be approved)
- Start of 1st operation: **2028**

The European Physical Journal

volume 229 · number 24 · December 2020

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Special Topics

EuPRAXIA Conceptual Design Report

Ralph Assmann and Maria Weikum (Eds.)

edp sciences

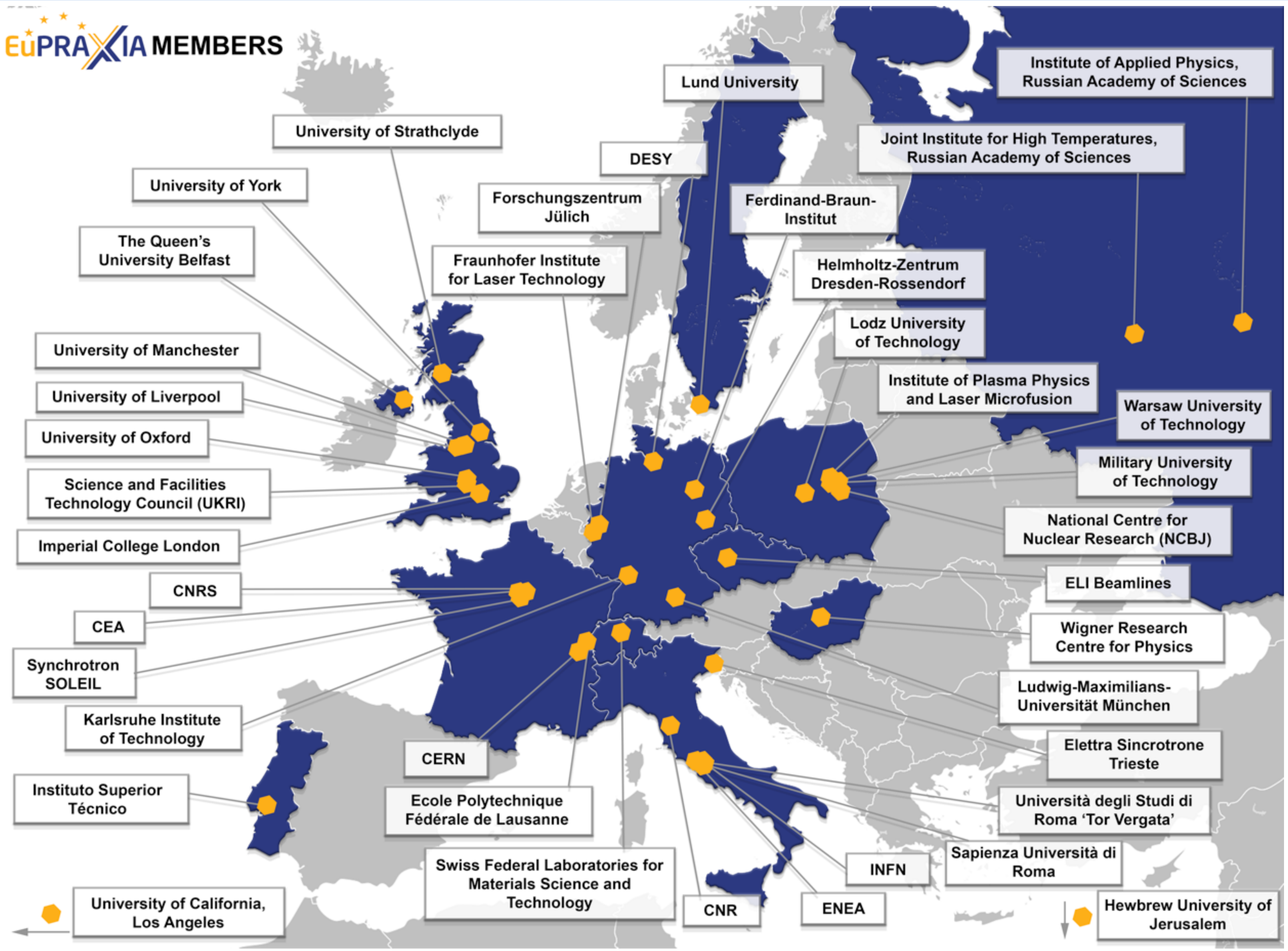
Springer

600+ page CDR, 240 scientists contributed

Consortium

(from 16 to 40 members in new Dec 2020 consortium)

Horizon 2020



40 Member institutions in:

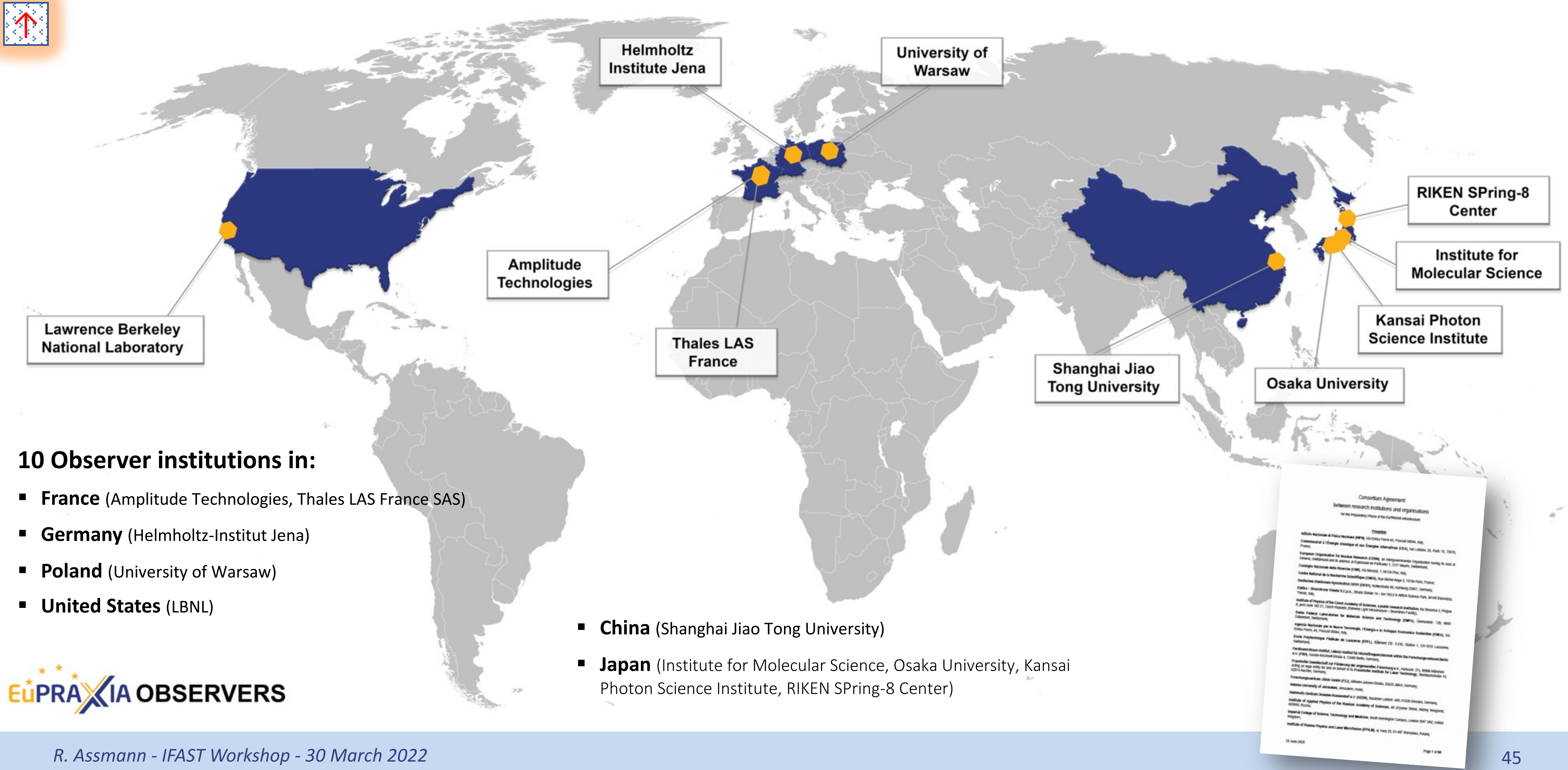
- **Italy** (INFN, CNR, Elettra, ENEA, Sapienza Università di Roma, Università degli Studi di Roma "Tor Vergata")
- **France** (CEA, SOLEIL, CNRS)
- **Switzerland** (EMPA, Ecole Polytechnique Fédérale de Lausanne)
- **Germany** (DESY, Ferdinand-Braun-Institut, Fraunhofer Institute for Laser Technology, Forschungszentrum Jülich, HZDR, KIT, LMU München)
- **United Kingdom** (Imperial College London, Queen's University of Belfast, STFC, University of Liverpool, University of Manchester, University of Oxford, University of Strathclyde, University of York)
- **Poland** (Institute of Plasma Physics and Laser Microfusion, Lodz University of Technology, Military University of Technology, NCBJ, Warsaw University of Technology)
- **Portugal** (IST)
- **Hungary** (Wigner Research Centre for Physics)
- **Sweden** (Lund University)
- **Israel** (Hebrew University of Jerusalem)
- **Russia** (Institute of Applied Physics, Joint Institute for High Temperatures)
- **United States** (UCLA)
- **CERN**
- **ELI Beamlines**

plus Spain & Greece

Consortium

(10 observer institutes)

Horizon 2020



10 Observer institutions in:

- **France** (Amplitude Technologies, Thales LAS France SAS)
- **Germany** (Helmholtz-Institut Jena)
- **Poland** (University of Warsaw)
- **United States** (LBNL)

- **China** (Shanghai Jiao Tong University)
- **Japan** (Institute for Molecular Science, Osaka University, Kansai Photon Science Institute, RIKEN SPring-8 Center)

EuPRAXIA OBSERVERS

Thanks to the scientists, many senior European leaders helping as work package leaders and finding the solutions

2015 in Hamburg

Kick-off meeting at DESY on Nov 26th – 27th

Thanks to the scientists, many senior European leaders helping as work package leaders and finding the solutions

2016 in Paris


Ecole polytechnique
2016 02 19

The EuPRAXIA Answers

Can plasma accelerators produce usable electron beams?

- **Yes**, we have designed a EuPRAXIA plasma accelerator facility that can produce usable beams.

For what can we use those beams while we increase the beam energy towards HEP and collider usages?

- There are several **highly attractive use cases**, in particular a **compact free-electron laser** but also superior X ray medical imaging and positron annihilation spectroscopy.

→ We are **ready to build a first, distributed user facility based on plasma accelerators**! Proposal to governments and European research area.


The European Physical Journal volume 229 · number 24 · December 2020
EPJ ST
Recognized by European Physical Society
Special Topics
EuPRAXIA Conceptual Design Report
Ralph Assmann and Maria Weikum (Eds.)
edp sciences Springer

600+ page CDR, 240 scientists contributed

Outline

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- EuPRAXIA Innovation
- EuPRAXIA ESFRI Features
- Towards Particle Physics
- Conclusion

EuPRAXIA facility rendering picture

The ESFRI Roadmap

ESFRI

NEW PROPOSAL SUBMISSION

1 — SEPTEMBER 2019

READ GUIDE & QUESTIONNAIRE
Read carefully the Roadmap Guide 2021 and the Questionnaire

DOCUMENTS
- Guide
- Questionnaire

available at www.esfri.eu

2 — INTERACTION WITH ESFRI DELEGATION
Interact with the LEAD ESFRI Delegation or EIROforum Member

3 — NATIONAL DEADLINES

CHECK ELIGIBILITY CRITERIA
Check national procedure and deadline to fulfill the Eligibility Criteria

PROOF
- EoS
- EoC
- MoU

4 — CHECK MINIMAL KEY REQUIREMENTS
Check compliance with MKRs for the Preparation Phase

5 — JANUARY 2020

FILL ONLINE QUESTIONNAIRE
Prepare online proposal

MOS
- Preliminary proposal
- Consolidated proposal

6 — SEPTEMBER 2020

FINALISATION & SUBMISSION

StR-ESFRI2 Funded by EU H2020

E uropean
S trategy
F orum on
R esearch
I nfrastructures

EOS = Expression of support
EOC = Expression of commitment

https://roadmap2021.esfri.eu

Press Release ESFRI 30.6.21

ESFRI

ABOUT ESFR

HOME › NEWS › LATEST ESFRI NEWS

ESFRI announces new RIs for Roa

30.06.2021

PRESS RELEASE

ESFRI announces the 11 new Researc included in its Roadmap 2021

€4.1 billion investment in excellent s European challenges

After two years of hard work, followin selection procedure, ESFRI proudly a have been scored high for their scienc implementation and will be included **2021 Roadmap Update**.

The new ESFRI Projects are:

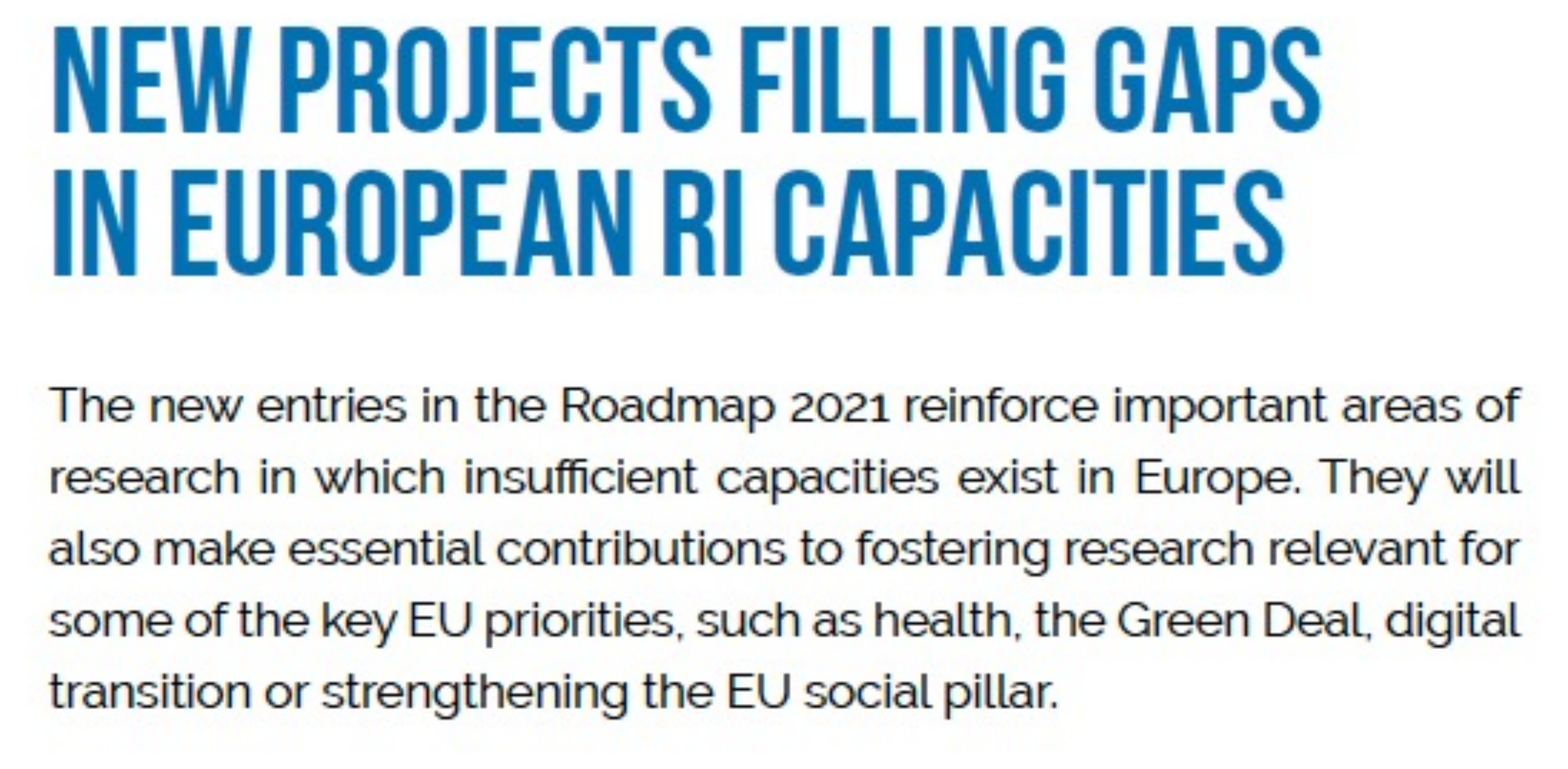
- There is a **new level of ambition** to develop globally unique, complex facilities for frontier science: Einstein Telescope – highest value project ever on the Roadmap - EUR 1.900 million, and EuPRAXIA – innovative accelerator based on plasma technology - EUR 569 million.

- **ET** - Einstein Telescope, the first and most advanced third-generation gravitational-wave observatory, with unprecedented sensitivity that will put Europe at the forefront of the Gravitation Waves research.
- **EuPRAXIA** - European Plasma Research Accelerator with Excellence in Applications, a distributed, compact and innovative accelerator facility based on plasma technology, set to construct an electron-beam-driven plasma accelerator in the metropolitan area of Rome, followed by a laser-driven plasma accelerator in European territory.

https://www.esfri.eu/latest-esfri-news/new-ris-roadmap-2021

First Plasma Accelerator Project on ESFRI

Horizon 2020



NEW PROJECTS FILLING GAPS IN EUROPEAN RI CAPACITIES

The new entries in the Roadmap 2021 reinforce important areas of research in which insufficient capacities exist in Europe. They will also make essential contributions to fostering research relevant for some of the key EU priorities, such as health, the Green Deal, digital transition or strengthening the EU social pillar.

https://roadmap2021.esfri.eu

ESFRI

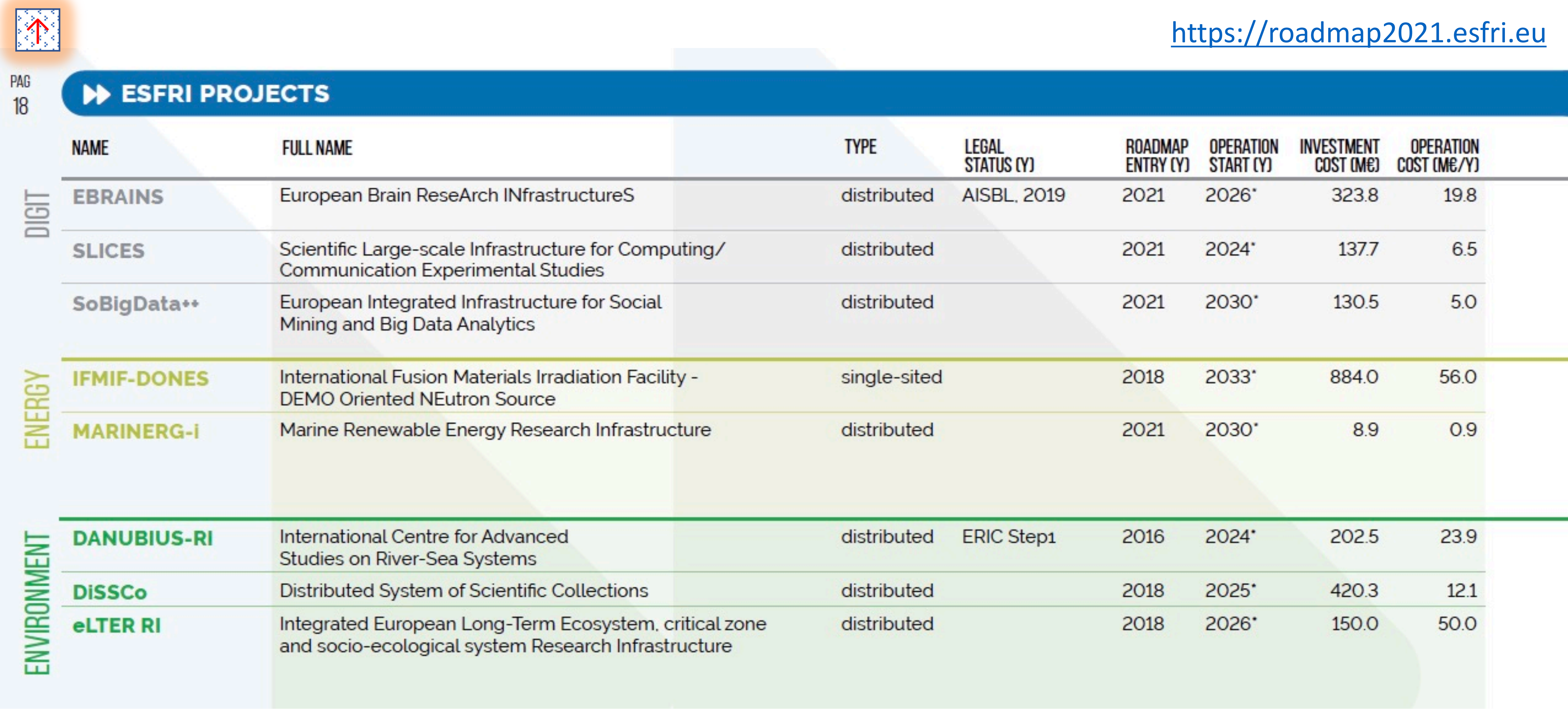
CHALLENGES AND STRATEGY FOR THE FUTURE

There is a growing need for new types of Research Infrastructures linked with specific challenges, like climate change and environmental sustainability, cutting across scientific disciplines. These RIs require multiple sites and mobile or virtual capacities. They need to be conceived and deployed not only in the EU but at a global scale that matches the scope of the targeted problems.

ESFRI Projects Roadmap 2021

Horizon 2020

https://roadmap2021.esfri.eu



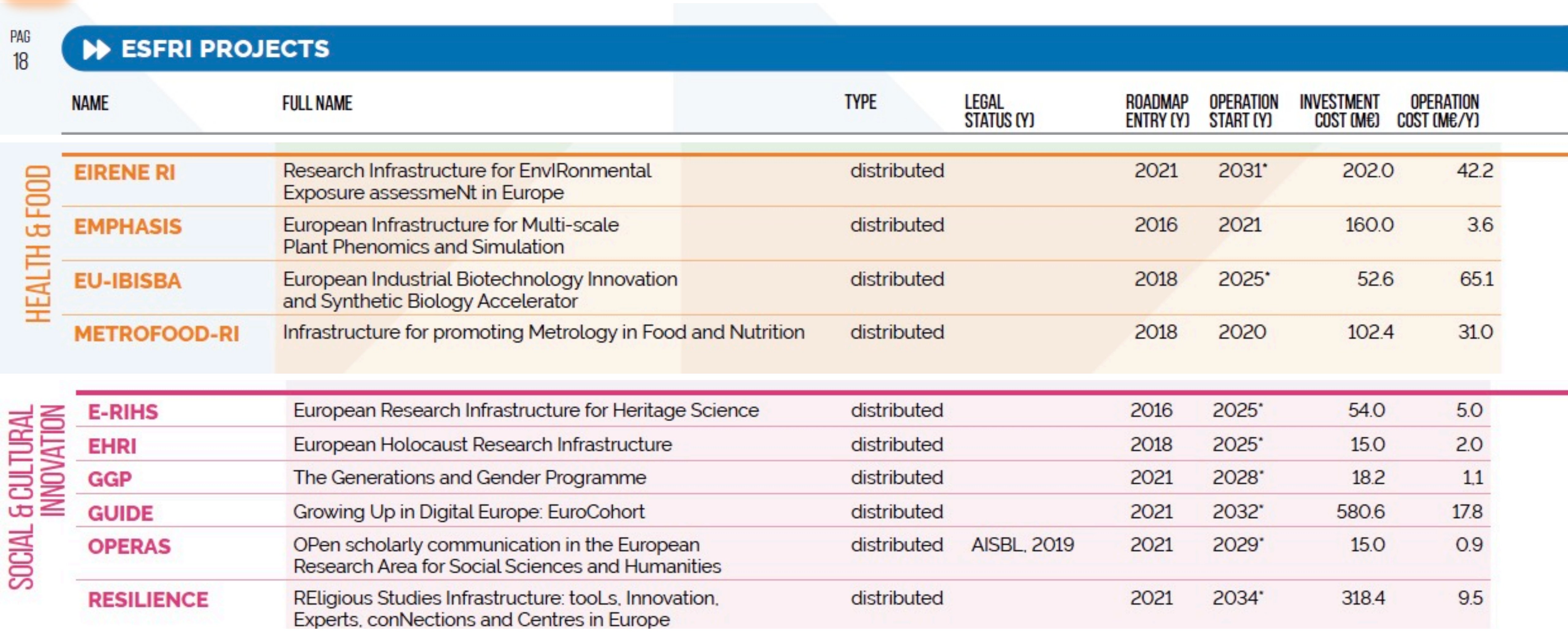
PAG 18

ESFRI PROJECTS

	NAME	FULL NAME	TYPE	LEGAL STATUS (Y)	ROADMAP ENTRY (Y)	OPERATION START (Y)	INVESTMENT COST (M€)	OPERATION COST (M€/Y)
DIGIT	**EBRAINS**	European Brain ReseArch INfrastructureS	distributed	AISBL, 2019	2021	2026*	323.8	19.8
	SLICES	Scientific Large-scale Infrastructure for Computing/ Communication Experimental Studies	distributed		2021	2024*	137.7	6.5
	SoBigData++	European Integrated Infrastructure for Social Mining and Big Data Analytics	distributed		2021	2030*	130.5	5.0
ENERGY	**IFMIF-DONES**	International Fusion Materials Irradiation Facility - DEMO Oriented NEutron Source	single-sited		2018	2033*	884.0	56.0
	MARINERG-i	Marine Renewable Energy Research Infrastructure	distributed		2021	2030*	8.9	0.9
ENVIRONMENT	**DANUBIUS-RI**	International Centre for Advanced Studies on River-Sea Systems	distributed	ERIC Step1	2016	2024*	202.5	23.9
	DiSSCo	Distributed System of Scientific Collections	distributed		2018	2025*	420.3	12.1
	eLTER RI	Integrated European Long-Term Ecosystem, critical zone and socio-ecological system Research Infrastructure	distributed		2018	2026*	150.0	50.0

ESFRI Projects Roadmap 2021

https://roadmap2021.esfri.eu



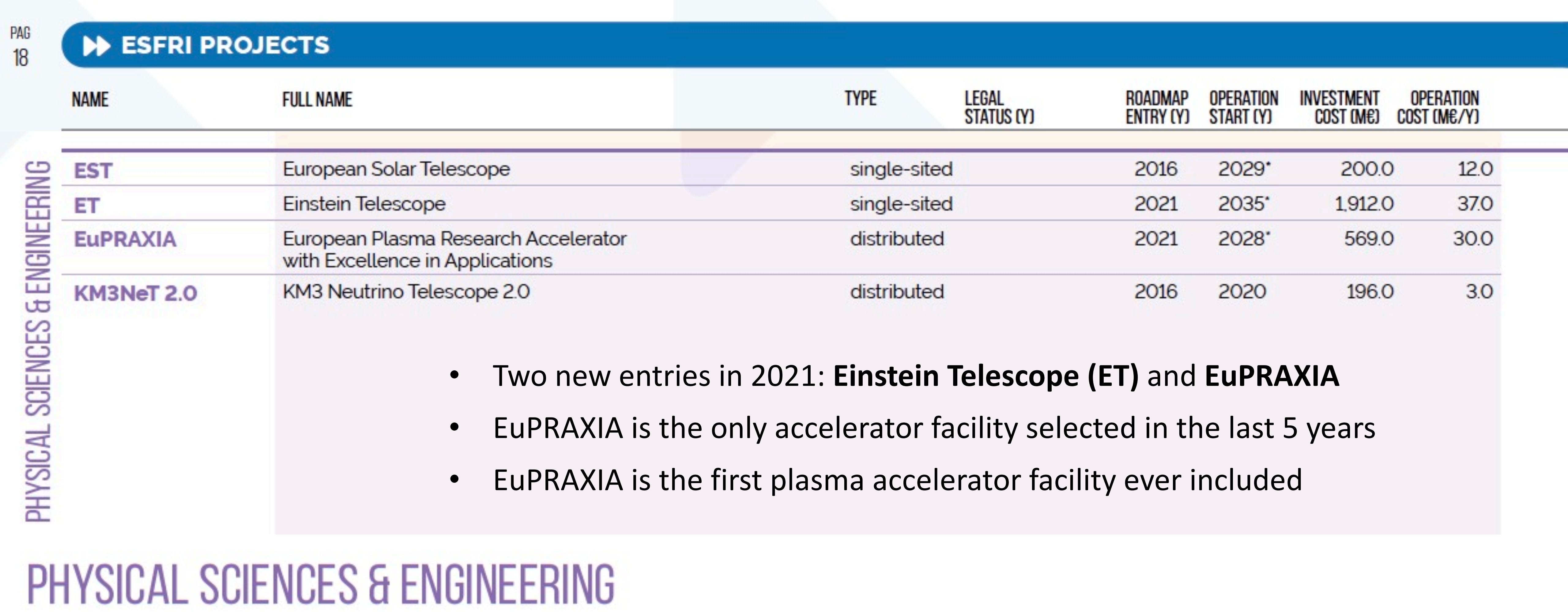
PAG 18

ESFRI PROJECTS

	NAME	FULL NAME	TYPE	LEGAL STATUS (Y)	ROADMAP ENTRY (Y)	OPERATION START (Y)	INVESTMENT COST (M€)	OPERATION COST (M€/Y)
HEALTH & FOOD	**EIRENE RI**	Research Infrastructure for EnvIRonmental Exposure assessmeNt in Europe	distributed		2021	2031*	202.0	42.2
	EMPHASIS	European Infrastructure for Multi-scale Plant Phenomics and Simulation	distributed		2016	2021	160.0	3.6
	EU-IBISBA	European Industrial Biotechnology Innovation and Synthetic Biology Accelerator	distributed		2018	2025*	52.6	65.1
	METROFOOD-RI	Infrastructure for promoting Metrology in Food and Nutrition	distributed		2018	2020	102.4	31.0
SOCIAL & CULTURAL INNOVATION	**E-RIHS**	European Research Infrastructure for Heritage Science	distributed		2016	2025*	54.0	5.0
	EHRI	European Holocaust Research Infrastructure	distributed		2018	2025*	15.0	2.0
	GGP	The Generations and Gender Programme	distributed		2021	2028*	18.2	1.1
	GUIDE	Growing Up in Digital Europe: EuroCohort	distributed		2021	2032*	580.6	17.8
	OPERAS	OPen scholarly communication in the European Research Area for Social Sciences and Humanities	distributed	AISBL, 2019	2021	2029*	15.0	0.9
	RESILIENCE	REligious Studies Infrastructure: tooLs, Innovation, Experts, conNections and Centres in Europe	distributed		2021	2034*	318.4	9.5

ESFRI Projects Roadmap 2021

https://roadmap2021.esfri.eu



PAG 18

ESFRI PROJECTS

PHYSICAL SCIENCES & ENGINEERING

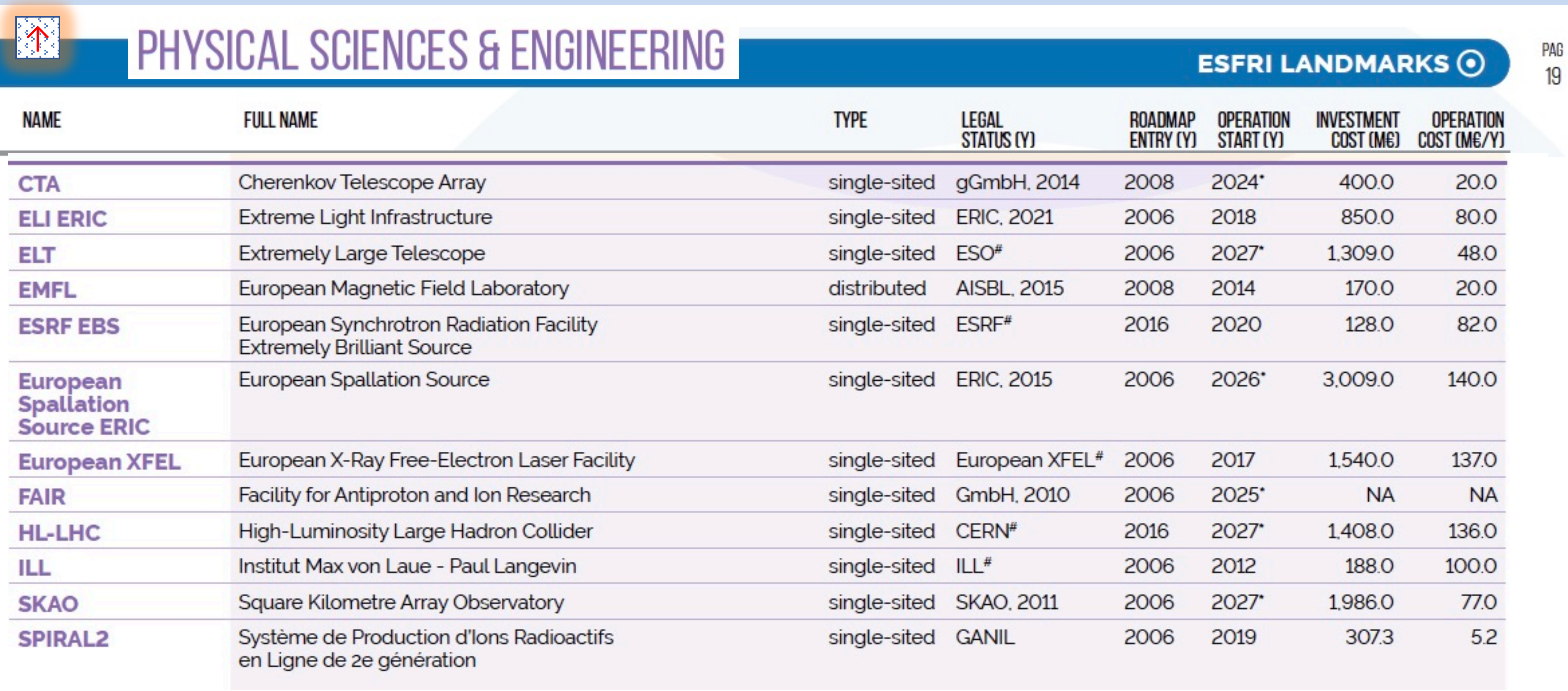
NAME	FULL NAME	TYPE	LEGAL STATUS (Y)	ROADMAP ENTRY (Y)	OPERATION START (Y)	INVESTMENT COST (M€)	OPERATION COST (M€/Y)
EST	European Solar Telescope	single-sited		2016	2029*	200.0	12.0
ET	Einstein Telescope	single-sited		2021	2035*	1,912.0	37.0
EuPRAXIA	European Plasma Research Accelerator with Excellence in Applications	distributed		2021	2028*	569.0	30.0
KM3NeT 2.0	KM3 Neutrino Telescope 2.0	distributed		2016	2020	196.0	3.0

PHYSICAL SCIENCES & ENGINEERING

- Two new entries in 2021: **Einstein Telescope (ET)** and **EuPRAXIA**
- EuPRAXIA is the only accelerator facility selected in the last 5 years
- EuPRAXIA is the first plasma accelerator facility ever included

ESFRI Landmarks Roadmap 2021

(Physical Sciences & Engineering)



PHYSICAL SCIENCES & ENGINEERING

ESFRI LANDMARKS

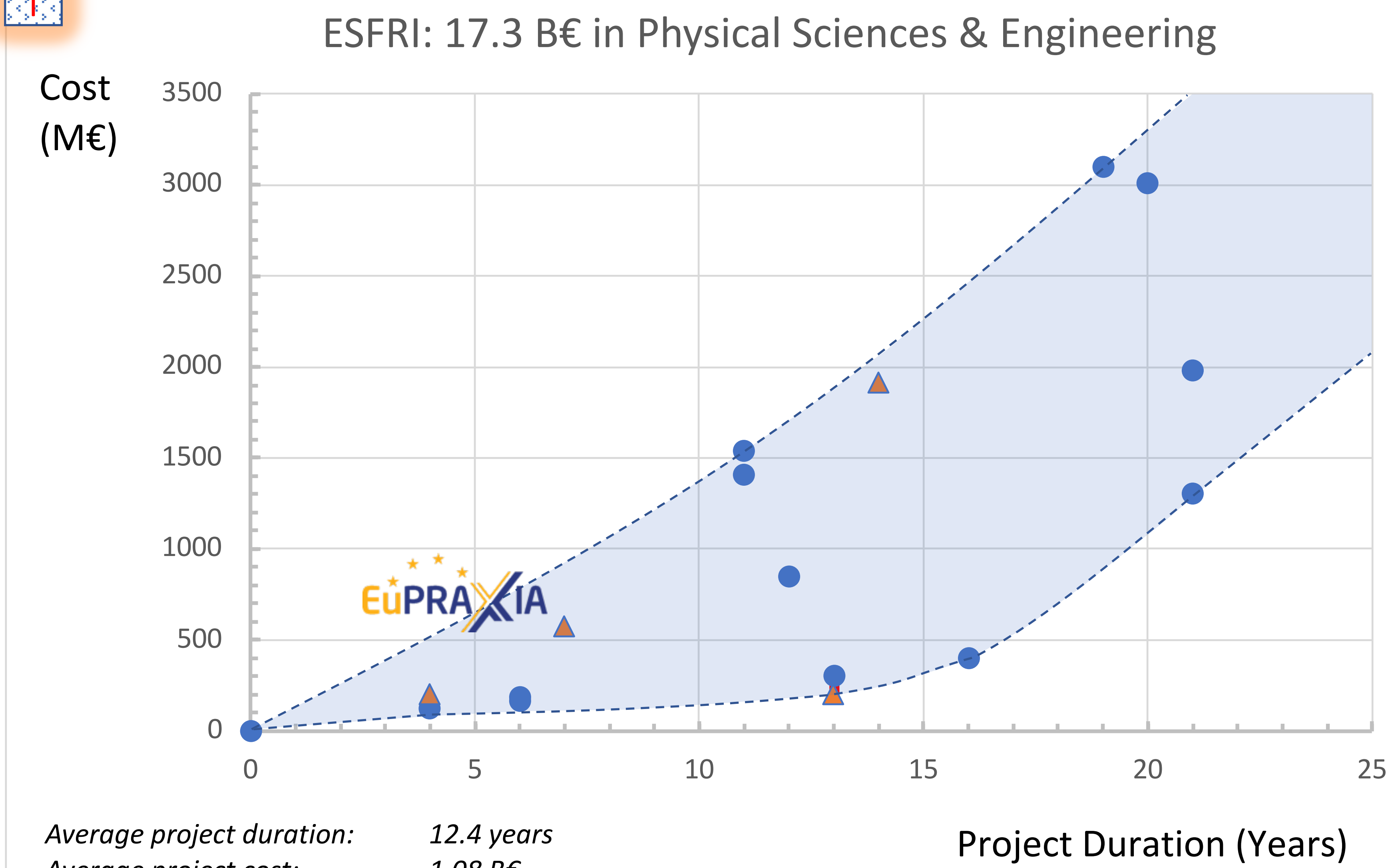
PAG 19

NAME	FULL NAME	TYPE	LEGAL STATUS (Y)	ROADMAP ENTRY (Y)	OPERATION START (Y)	INVESTMENT COST (M€)	OPERATION COST (M€/Y)
CTA	Cherenkov Telescope Array	single-sited	gGmbH, 2014	2008	2024*	400.0	20.0
ELI ERIC	Extreme Light Infrastructure	single-sited	ERIC, 2021	2006	2018	850.0	80.0
ELT	Extremely Large Telescope	single-sited	ESO#	2006	2027*	1,309.0	48.0
EMFL	European Magnetic Field Laboratory	distributed	AISBL, 2015	2008	2014	170.0	20.0
ESRF EBS	European Synchrotron Radiation Facility Extremely Brilliant Source	single-sited	ESRF#	2016	2020	128.0	82.0
European Spallation Source ERIC	European Spallation Source	single-sited	ERIC, 2015	2006	2026*	3,009.0	140.0
European XFEL	European X-Ray Free-Electron Laser Facility	single-sited	European XFEL#	2006	2017	1,540.0	137.0
FAIR	Facility for Antiproton and Ion Research	single-sited	GmbH, 2010	2006	2025*	NA	NA
HL-LHC	High-Luminosity Large Hadron Collider	single-sited	CERN#	2016	2027*	1,408.0	136.0
ILL	Institut Max von Laue - Paul Langevin	single-sited	ILL#	2006	2012	188.0	100.0
SKAO	Square Kilometre Array Observatory	single-sited	SKAO, 2011	2006	2027*	1,986.0	77.0
SPIRAL2	Système de Production d'Ions Radioactifs en Ligne de 2e génération	single-sited	GANIL	2006	2019	307.3	5.2

https://roadmap2021.esfri.eu

ESFRI Roadmap 2021

(Physical Sciences & Engineering – Projects Red Triangles)



Average project duration: *12.4 years*
Average project cost: *1.08 B€*

Accelerator Facilities
- 10.1 B€ invest
- 730 M€ OP / year

Telescopes
- 6.0 B€ invest
- 197 M€ OP / year

Laser Facilities (ELI)
- 0.85 B€ invest
- 80 M€ OP / year

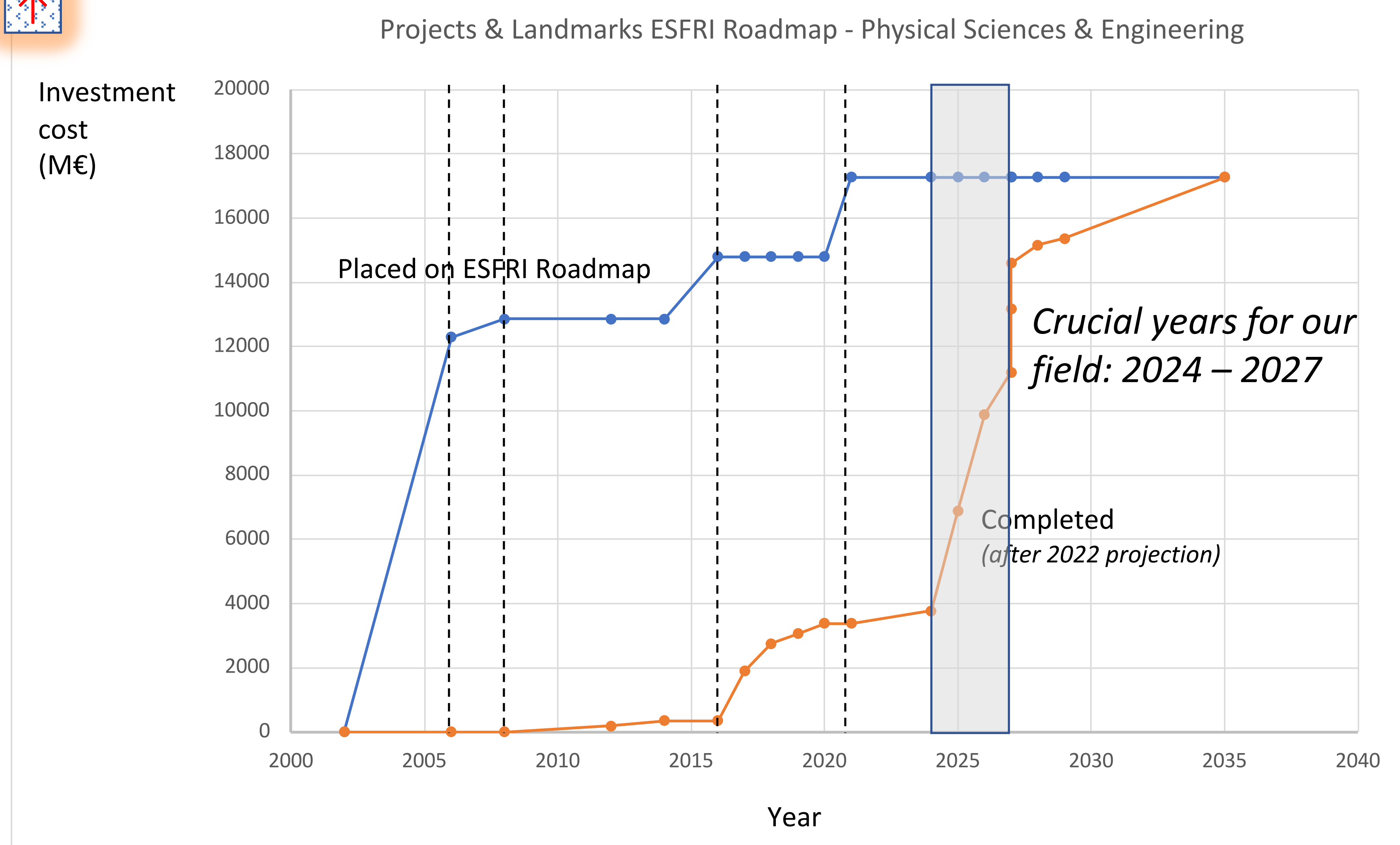
Reactor neutrons (ILL)
- 0.19 B€ invest
- 100 M€ OP / year

Magnet lab (EMFL)
- 0.17 B€ invest
- 20 M€ OP / year

Putting Projects into Operation

(Physical Sciences & Engineering – Projects Red Triangles)

Horizon 2020



Crucial years for our field: 2024 – 2027

Accelerator Facilities	10.1 B€ invest 730 M€ OP / year
Telescopes	6.0 B€ invest 197 M€ OP / year
Laser Facilities (ELI)	0.85 B€ invest 80 M€ OP / year
Reactor neutrons (ILL)	0.19 B€ invest 100 M€ OP / year
Magnet lab (EMFL)	0.17 B€ invest 20 M€ OP / year

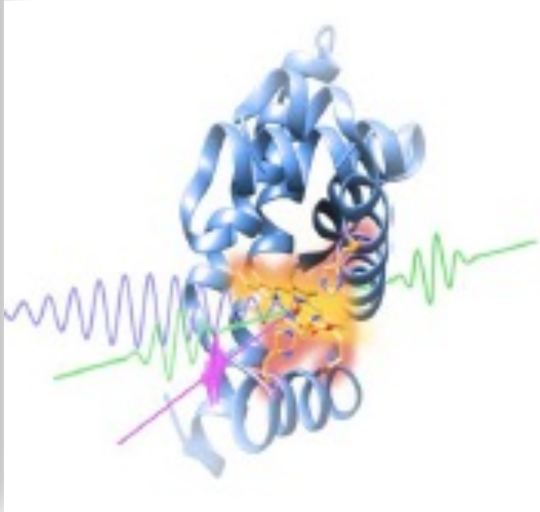
Outline

- The Plasma Accelerator Context
- The EuPRAXIA Objective
- ESFRI and EuPRAXIA
- **EuPRAXIA as a User Facility**
- EuPRAXIA Implementation
- EuPRAXIA Innovation
- EuPRAXIA ESFRI Features
- Towards Particle Physics
- Conclusion

Versatile – Designed for Users in Multiple Science Fields

EuPRAXIA delivers:

Ultra-short pulses of X rays, up to 5 GeV electrons, high energy positrons



proteins, viruses, bacteria, cells, metals, semiconductors, superconductors, magnetic materials, organic molecules

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Probing for New Particles and Forces

Horizon2020

Higgs Seminar 4.7. 2012

THE TIMES

Higgs celebrates 'God particle' discovery

27 km LHC at CERN

Understanding fundamental laws

Producing X Rays for Inspection

Horizon2020

Nuctech (China)

X-Ray radiography – Cargo inspection with a compact 6 MeV linear electron accelerator

Varian, USA

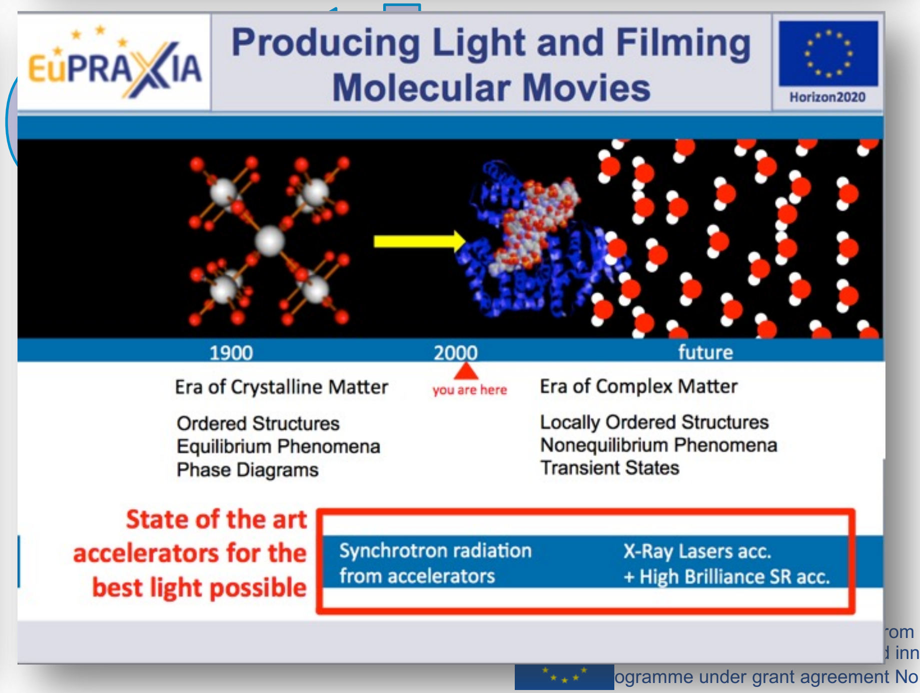
Protecting people

Irradiating and Destroying Tumor Cells

Horizon2020

Heidelberg Ion-Beam Therapy Center (HIT)

Curing people



Producing Light and Filming Molecular Movies

Horizon2020

1900 | 2000 | future

you are here

Era of Crystalline Matter	Era of Complex Matter
Ordered Structures Equilibrium Phenomena Phase Diagrams	Locally Ordered Structures Nonequilibrium Phenomena Transient States

State of the art accelerators for the best light possible

Synchrotron radiation from accelerators

X-Ray Lasers acc. + High Brilliance SR acc.

rom the European
d innovation
ogramme under grant agreement No 653782.

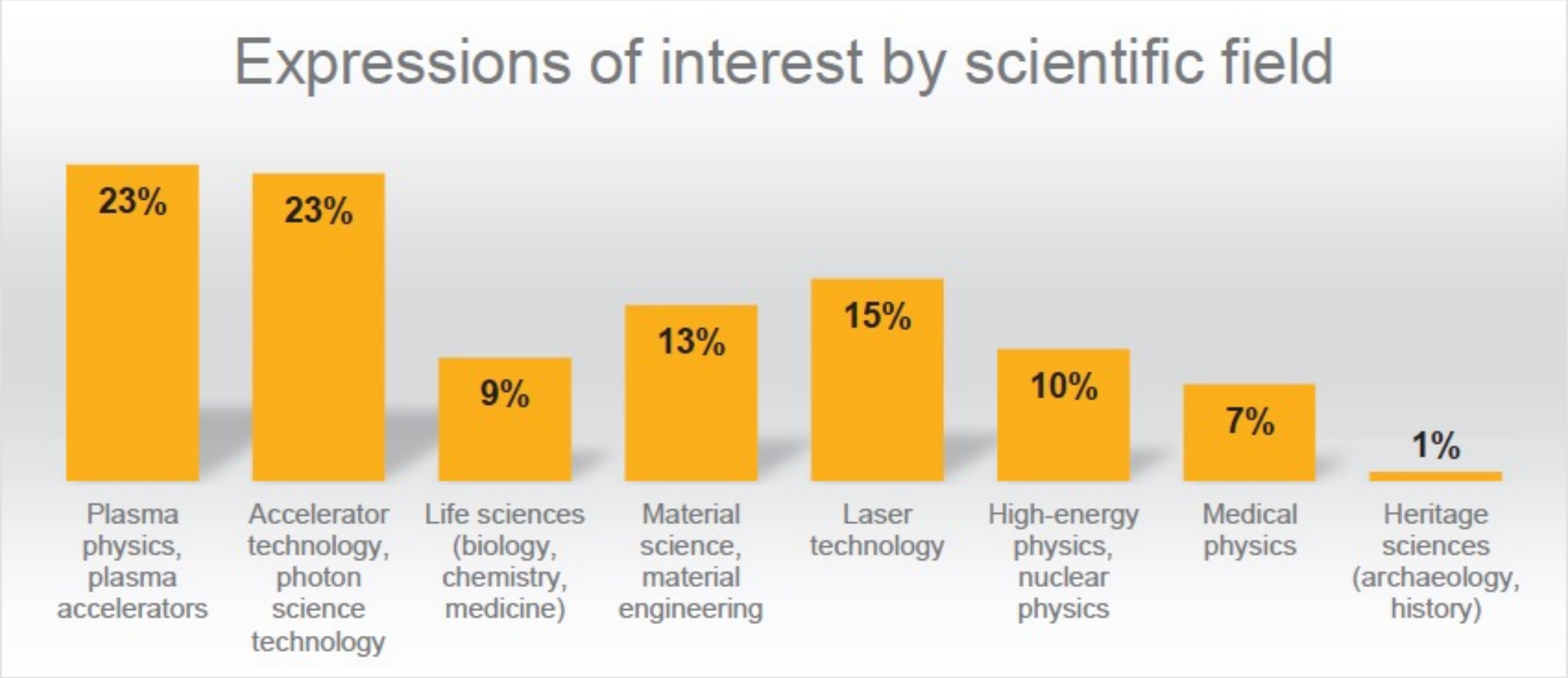
EuPRAXIA Deliverables and User Interests

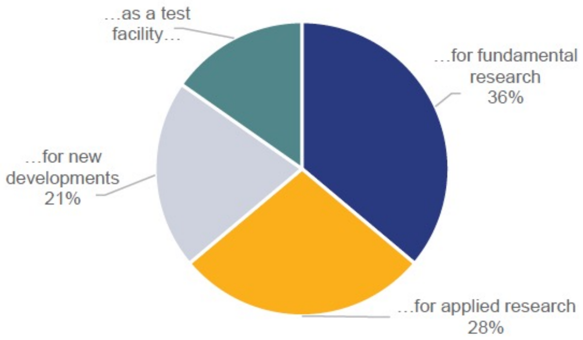
Horizon 2020

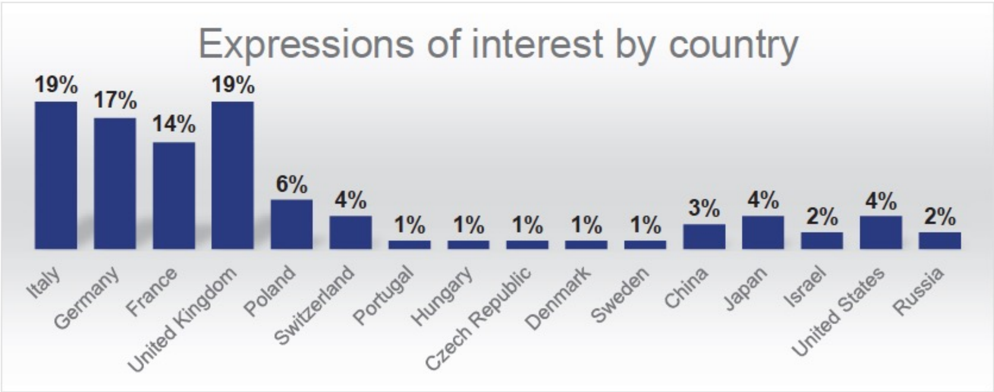
EuPRAXIA is designed to deliver at 10-100 Hz ultra-short pulses of

- Electrons (0.1-5 GeV, 30 pC)
- Positrons (0.5-10 MeV, 10^6)
- Positrons (GeV source)
- Lasers (100 J, 50 fs, 10-100 Hz)
- Betatron X rays (5-18 keV, 10^{10})
- FEL light (0.2-36 nm, 10^9-10^{13})

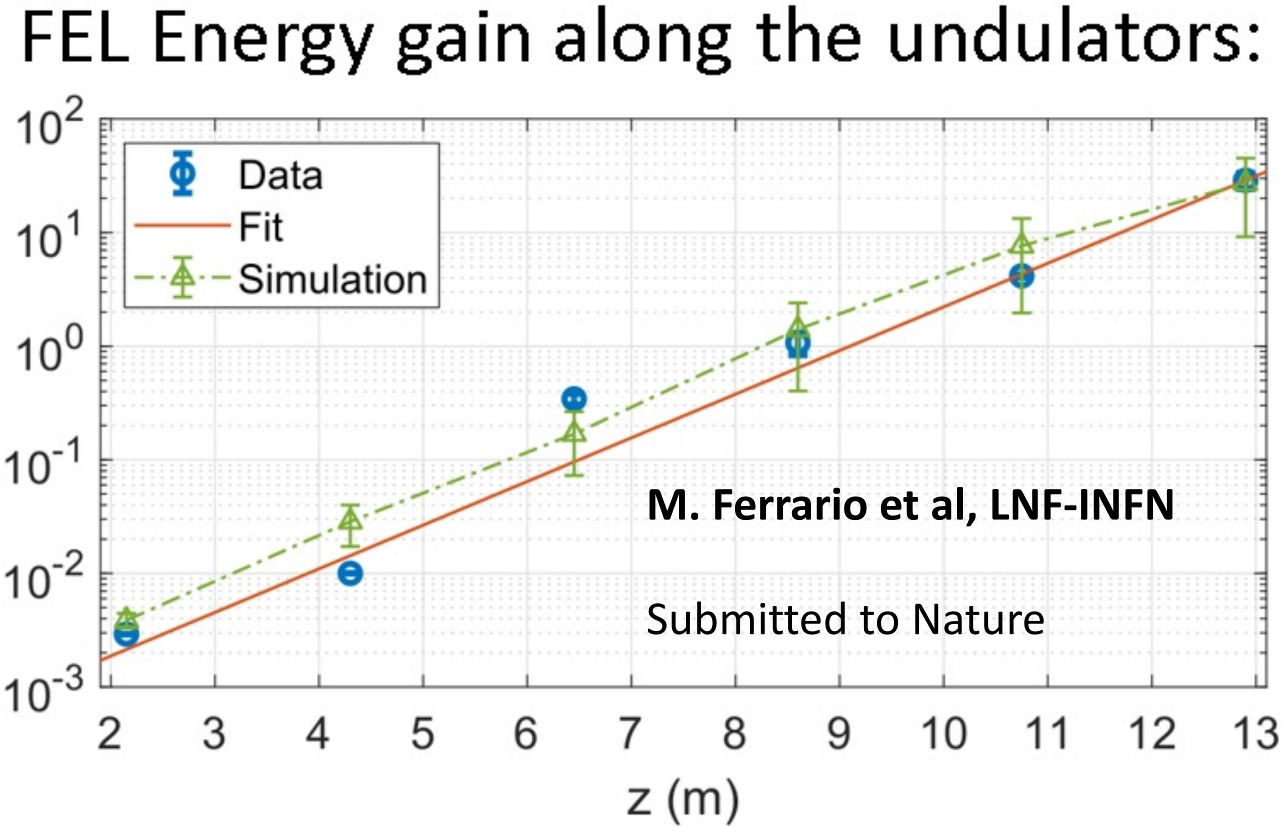
Expressions of interest from **95 research groups** representing several thousand scientists in total.







Functionality Demonstrated: Free Electron Laser



M. Ferrario et al, LNF-INFN

Submitted to Nature

Breakthrough LNF, SIOM:

Experimental proof that plasma accelerated electron beams are good enough for free-electron lasers (and colliders?)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Already working today: Medical Imaging

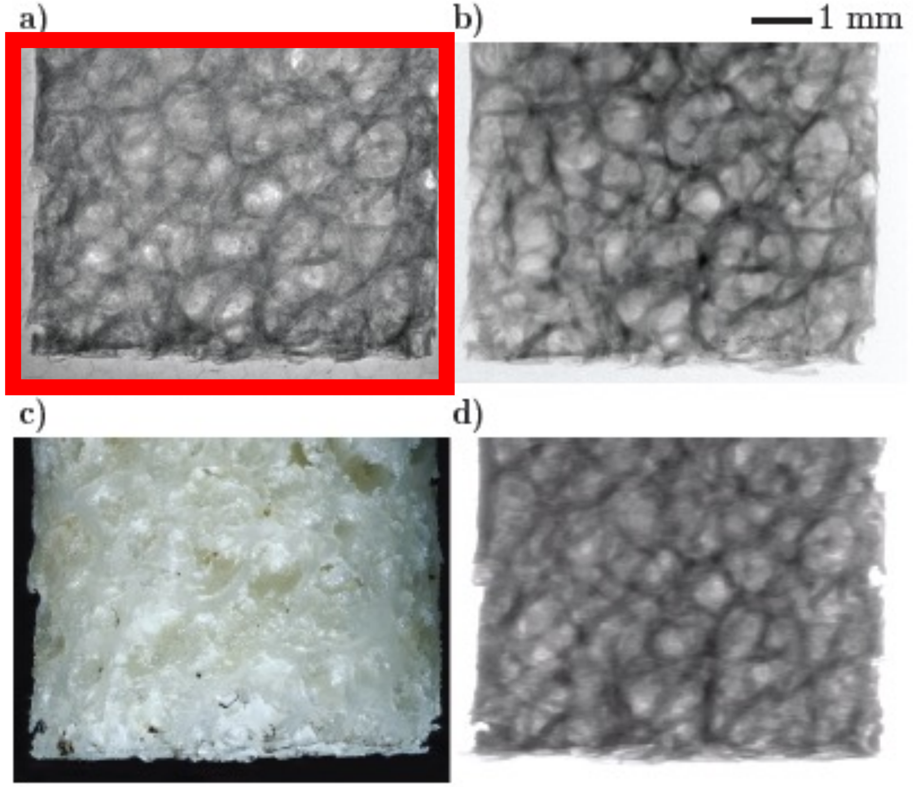
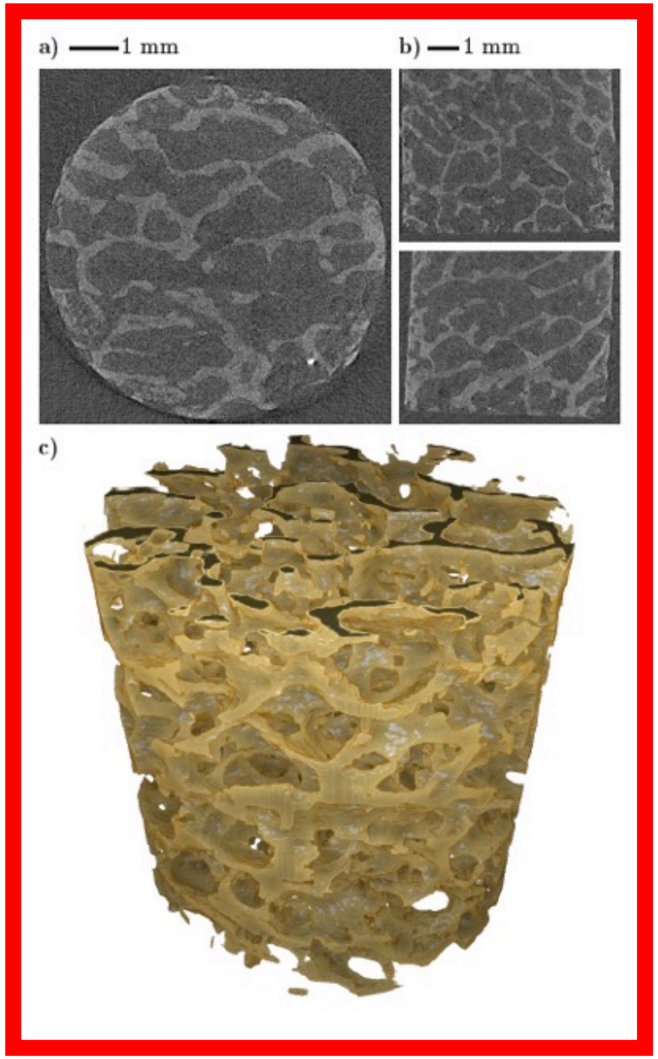
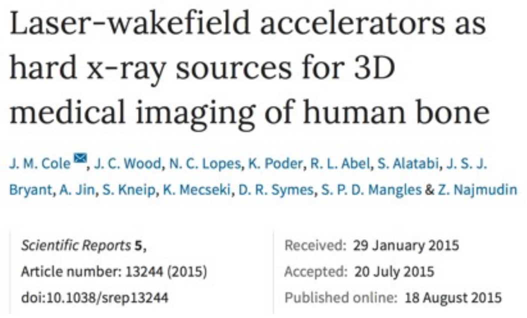


Figure 3. Images of the bone sample recorded with a) the betatron x-ray source b) conventional μCT scanning c) composite macro photography d) virtual illumination of the 3D reconstruction by a source of $E_{crit} = 33\,\mathrm{keV}$.





Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone

J. M. Cole, J. C. Wood, N. C. Lopes, K. Poder, R. L. Abel, S. Alatabi, J. S. J. Bryant, A. Jin, S. Kneip, K. Mecseki, D. R. Symes, S. P. D. Mangles & Z. Najmudin

Scientific Reports **5**,
Article number: 13244 (2015)
doi:10.1038/srep13244

Received: 29 January 2015
Accepted: 20 July 2015
Published online: 18 August 2015

from J.M. Cole et al, John-Adams-Institute, UK

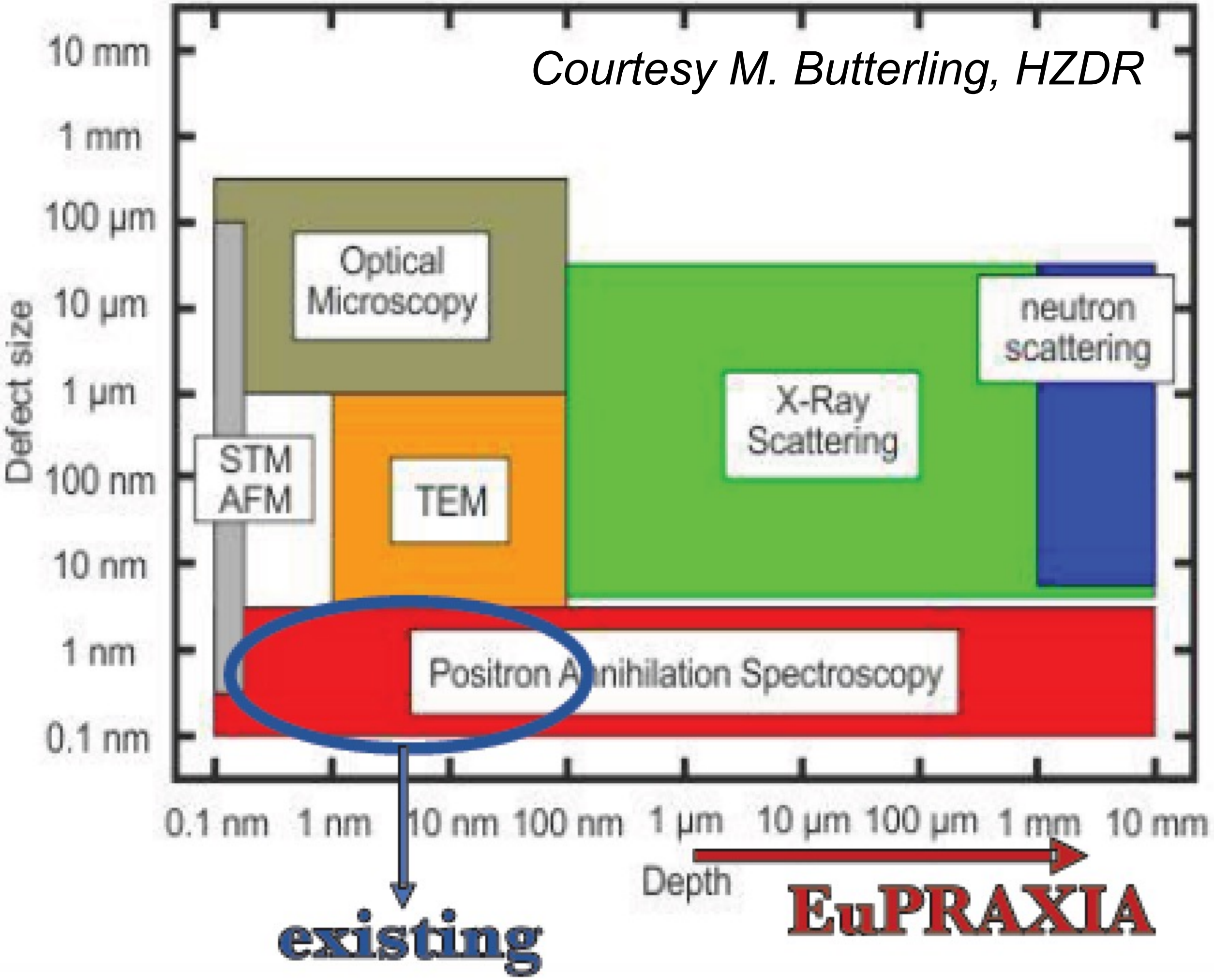
Laser plasma based betatron X ray source

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 653782.

Fully plasma-based beamline for generating betatron radiation as a ***compact X-ray source for medical imaging and material analysis****.*
The user area is behind the wall on the right.

EuPRAXIA facility rendering picture

Positron Annihilation Spectroscopy



Quantity	Baseline Value
Low-Energy Positron Source	
Positron energy	0.5–10 MeV (tunable)
Energy bandwidth	±50 keV
Beam duration	20–90 ps
Beam size at user area	2–5 mm
Positrons per shot	$\geq 10^6$

- EuPRAXIA would provide access to unique regime of detecting small defects at large penetration depths
- Does not require highest quality of electron beam

Gianluca Sarri et al

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

*Fully plasma-based beamline for generating **electron and positron beams**. The accelerator stages can be seen in the front. In the back the beamline splits and leads to two user areas behind the back wall.*

EuPRAXIA facility rendering picture

Outline

- The Plasma Accelerator Context
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- EuPRAXIA Innovation
- EuPRAXIA ESFRI Features
- Towards Particle Physics
- Conclusion

Advisory & Oversight Boards

- Open Innovation Forum
- Scientific & Technical Advisory Committee
- User Meetings & Program Committees
- Resource Review Board
- Quality Assurance Panel
- Ethical Advisory Board

Collaboration Board

1 representative per Member & Observer
1 Chair and 1 Deputy Chair

Co-funded by the European Union

Project Coordinator + Management Team

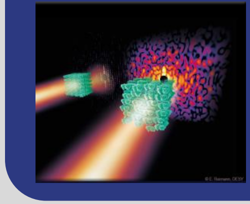
Steering Committee

Central EuPRAXIA Management

Construction Site Frascati

Local Project Team

Beam-driven plasma accelerator
Delivers FEL light, X rays, electrons, positrons
Life sciences, particle physics, medicine, materials



Location: metropolitan area Rome, Italy

Construction Site

(tbd in 2023)

Local Project Team

Laser-driven plasma accelerator
Delivers FEL light, X rays, electrons, positrons
Life sciences, medicine, materials

Four candidate sites described in conceptual design report

Excellence Centres

Local Project Teams

- *Plasma Simulations & Theory*
- *Laser-Plasma Acceleration & FEL Developments*
- *Plasma Acceleration & High-Rep-Rate Developments*
- *Advanced Application Beamlines*
- *Technology Incubator to Laser Science Users*

Technical design tests, prototyping, production

- *EuPRAXIA user e-needs infrastructure*

Project Clusters (WPs)

- *Theory & Simulation*
- *Laser Technology*
- *Plasma Components & Systems*
- *RF Technology*
- *Magnets & Other Beamline Components*
- *Diagnostics*
- *Applications*
- *Transformative Innovation Paths*
- *Training, Outreach & Dissemination*
- *Implementation & Layout*

Technical Design Report

National projects and facilities

Individual groups at universities and laboratories

Organization for initial Preparatory Phase in dark blue

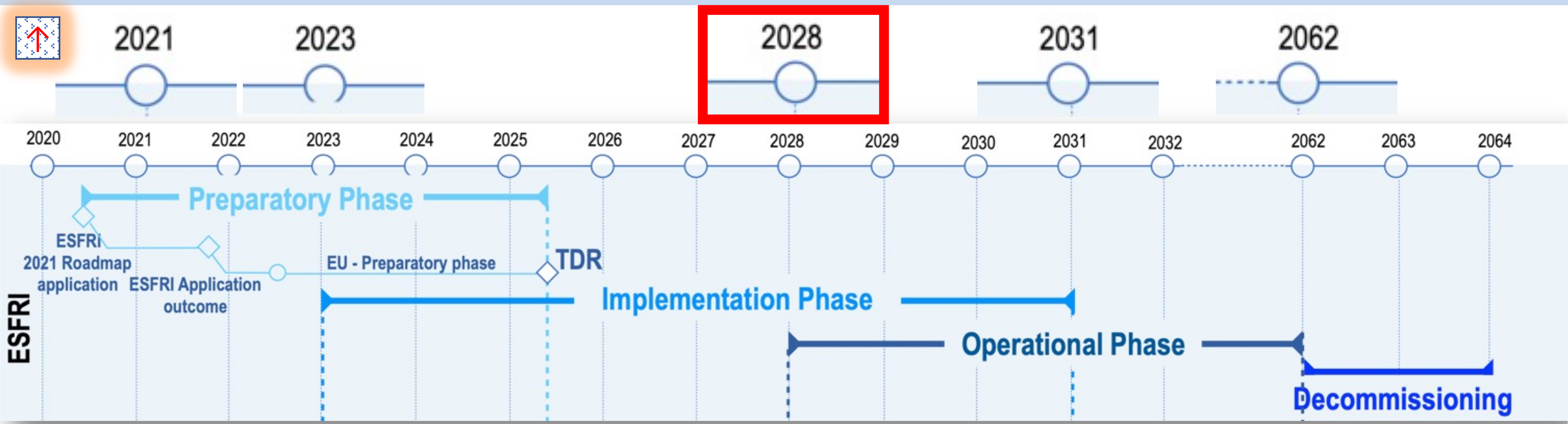
Features to be added with decision on second site or in later phases are indicated in lighter shades

Horizon 2020

Implementation

EuPRAXIA Schedule

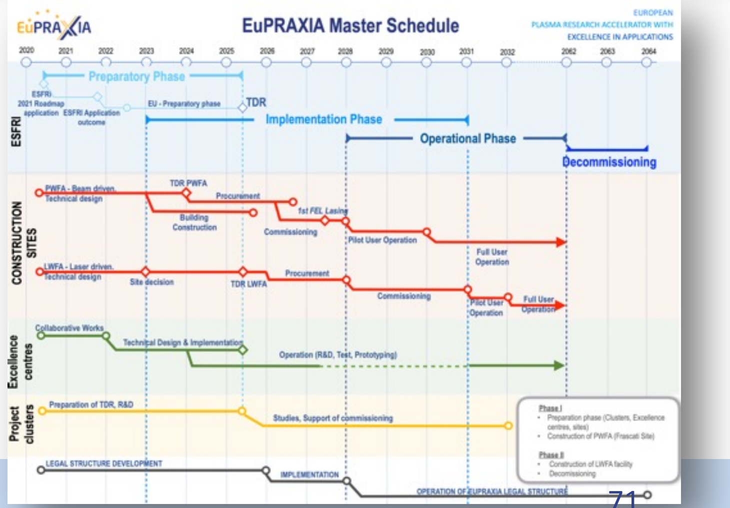
Horizon 2020



SUCCESS – ON TRACK

European World-Class RI on compact accelerators for the end of the 2020‘s to the beginning of the 2060‘s

More detail in Master Schedule

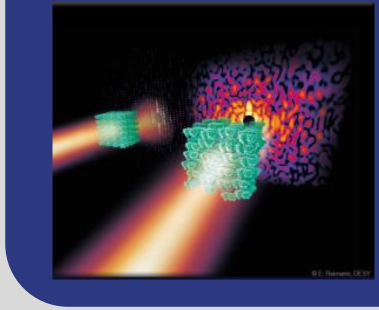


Concept Distributed Research Infrastructure

Construction Site Frascati

Local Project Team

Beam-driven plasma accelerator
Delivers FEL light, X rays, electrons, positrons
Life sciences, particle physics, medicine, materials



Location: metropolitan area Rome, Italy

Construction Site

(tbd in 2023)

Local Project Team

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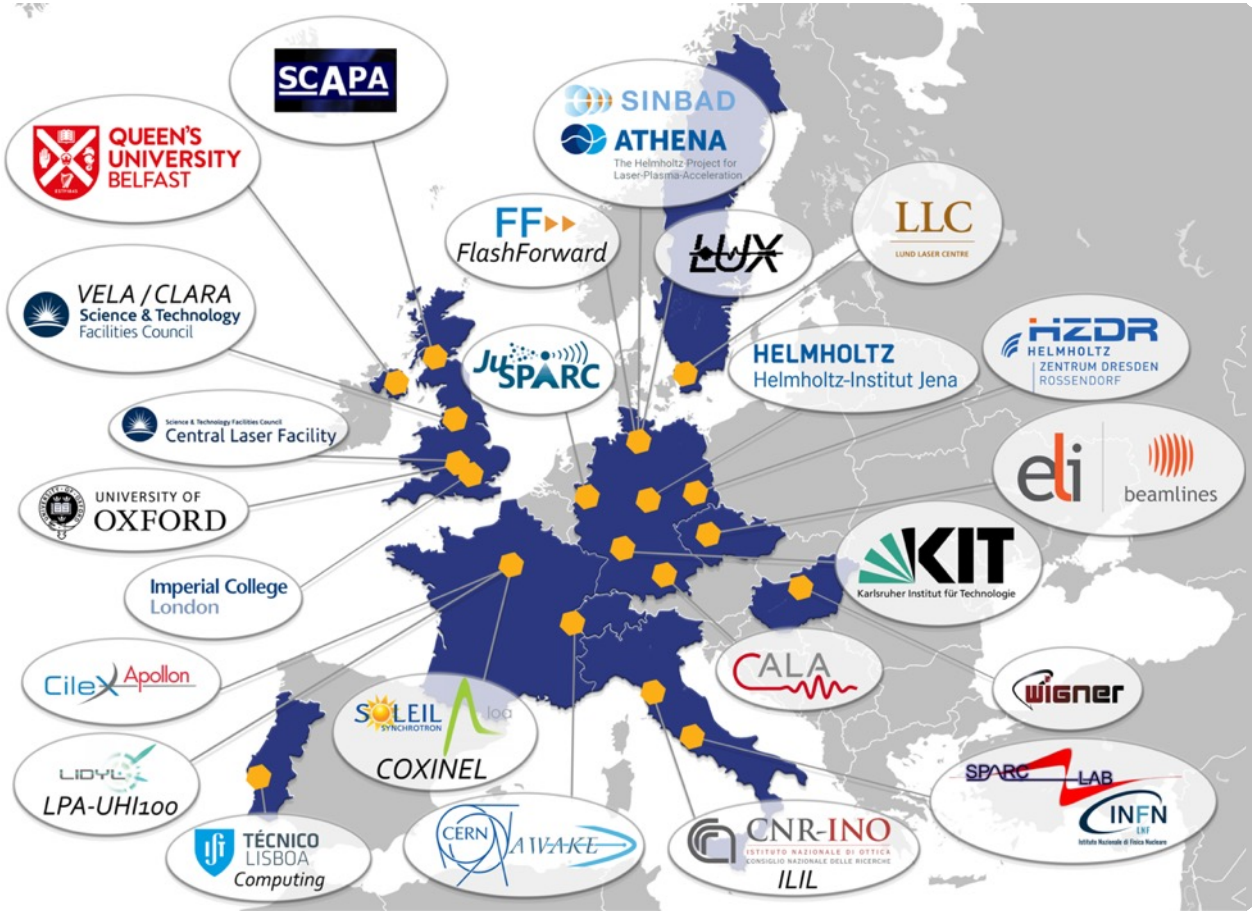
- *Advanced Application Beamlines*
- *Technology Incubator to Laser Science Users*

Technical design tests, prototyping, production

- *EuPRAXIA user e-needs infrastructure*

Single-Entry Point for Access, Alignment of European Resources



Bringing benefits of compact technology to **external users**

Alignment of scientific goals & resources

EuPRAXIA

Single point of access under EuPRAXIA rules

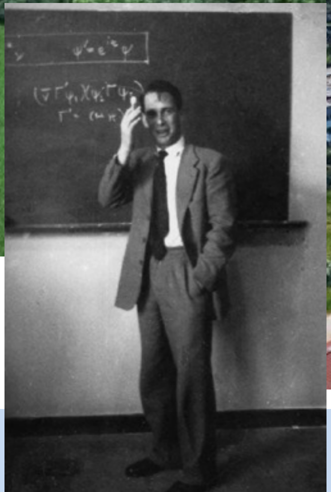
Policy of open innovation and **open science**

Defending and strengthening **EU leadership** in this field *(world-wide 1st RI concept of this kind)*

Site 1: EuPRAXIA@SPARClab

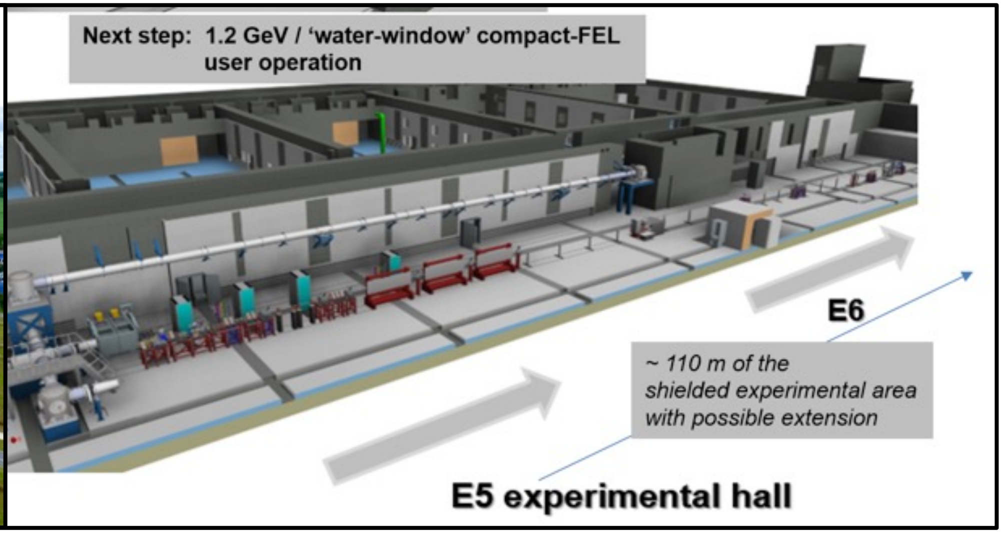
Horizon 2020

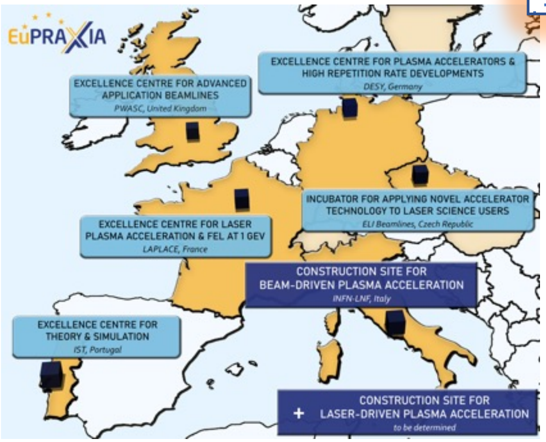
- Frascati`s future facility
- > 108 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)



Reminder: Candidate 2nd Sites from CDR

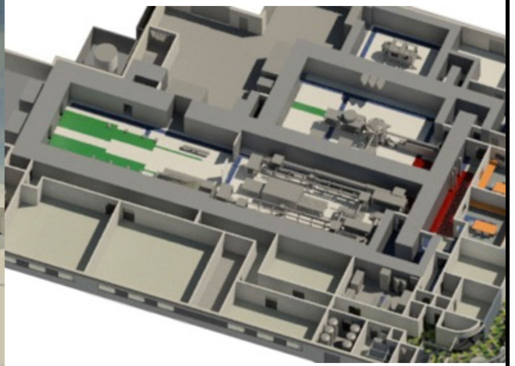
Prague,
Czech
Republic





EuPRAXIA @ EPAC

Rutherford, STFC, UK



CNR Campus Pisa

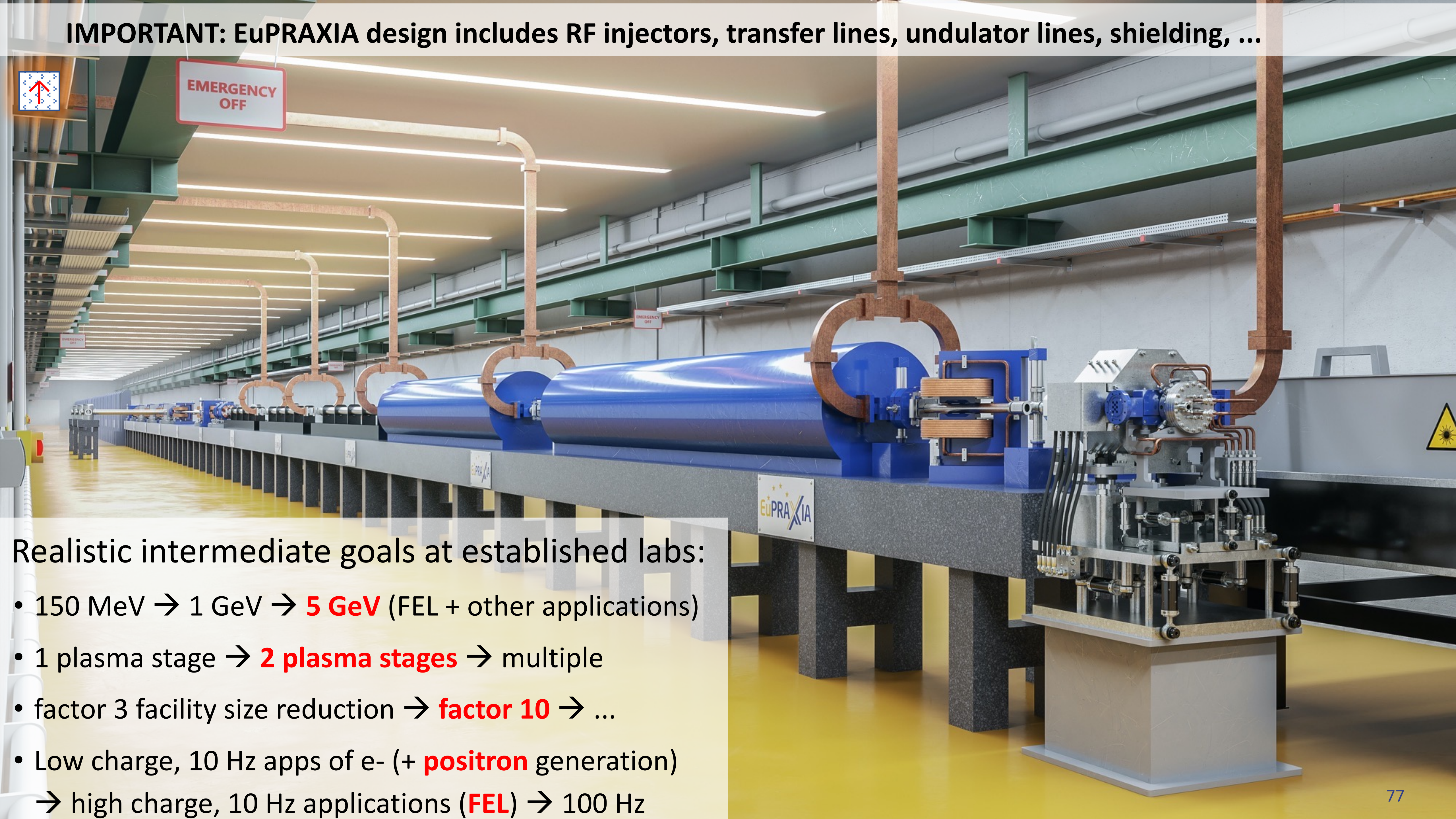
Selection Criteria 2nd EuPRAXIA Site

(from CDR, fulfilled by 1st Site LNF/INFN)

Legal/Political	Technical	Financial
Compliance of host institution with **EuPRAXIA Access** Policy	Site provides sufficient **space** (about 175 m x 35 m)	Commitment to **sustainability** of EuPRAXIA (host lab covers site operation costs)
Compliance of host institution with **EuPRAXIA Open Innovation** and **Open Science** Policy	Laboratory has **infrastructures** in one or several of RF accelerators, laser installations, user access.	**Previous investments** into local infrastructures of relevance for EuPRAXIA (leverage effect)
Agreement of host institution with the **long-term scientific agenda** of EuPRAXIA	Site provides required **services** and facilities for support of external users, including E infrastructure	Existence of one or a mix of **funding sources** able to finance implementation of the site
Laboratory has existing groups in place to guarantee **safety** requirements (laser, radio-protection, access control) and rules		

Note: approach reduces cost (pre-invest) and risks of cost-overun.

IMPORTANT: EuPRAXIA design includes RF injectors, transfer lines, undulator lines, shielding, ...



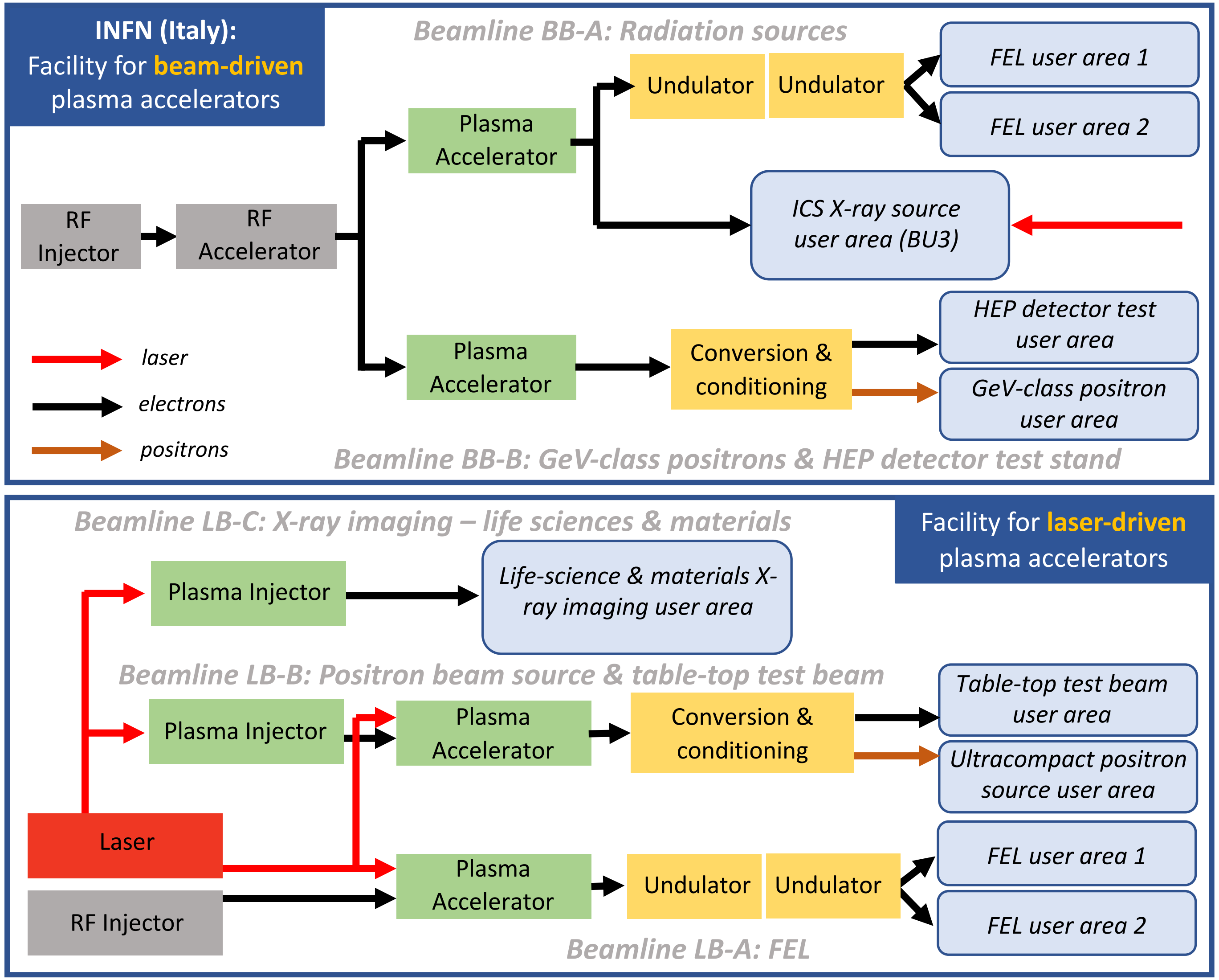
Realistic intermediate goals at established labs:

- 150 MeV → 1 GeV → **5 GeV** (FEL + other applications)
- 1 plasma stage → **2 plasma stages** → multiple
- factor 3 facility size reduction → **factor 10** → ...
- Low charge, 10 Hz apps of e- (+ **positron** generation)
  → high charge, 10 Hz applications (**FEL**) → 100 Hz

Phased Implementation of Construction Sites

Horizon 2020

Consider a phased implementation of beamlines and user areas to reduce risks and control costs better



INFN (Italy):
Facility for **beam-driven** plasma accelerators

Beamline BB-A: Radiation sources

Beamline BB-B: GeV-class positrons & HEP detector test stand

Beamline LB-C: X-ray imaging – life sciences & materials

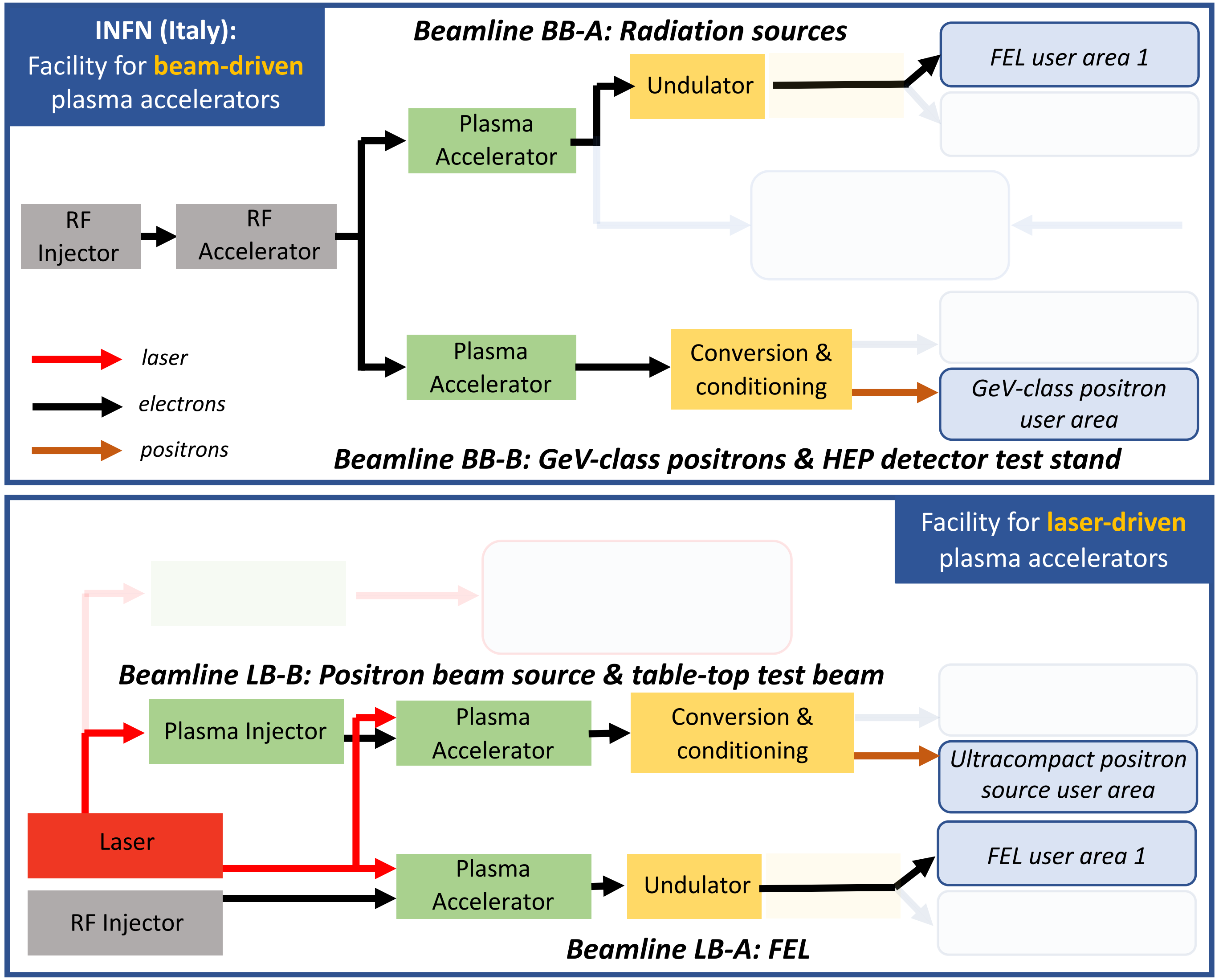
Facility for **laser-driven** plasma accelerators

Beamline LB-B: Positron beam source & table-top test beam

Beamline LB-A: FEL

Phased Implementation of Construction Sites

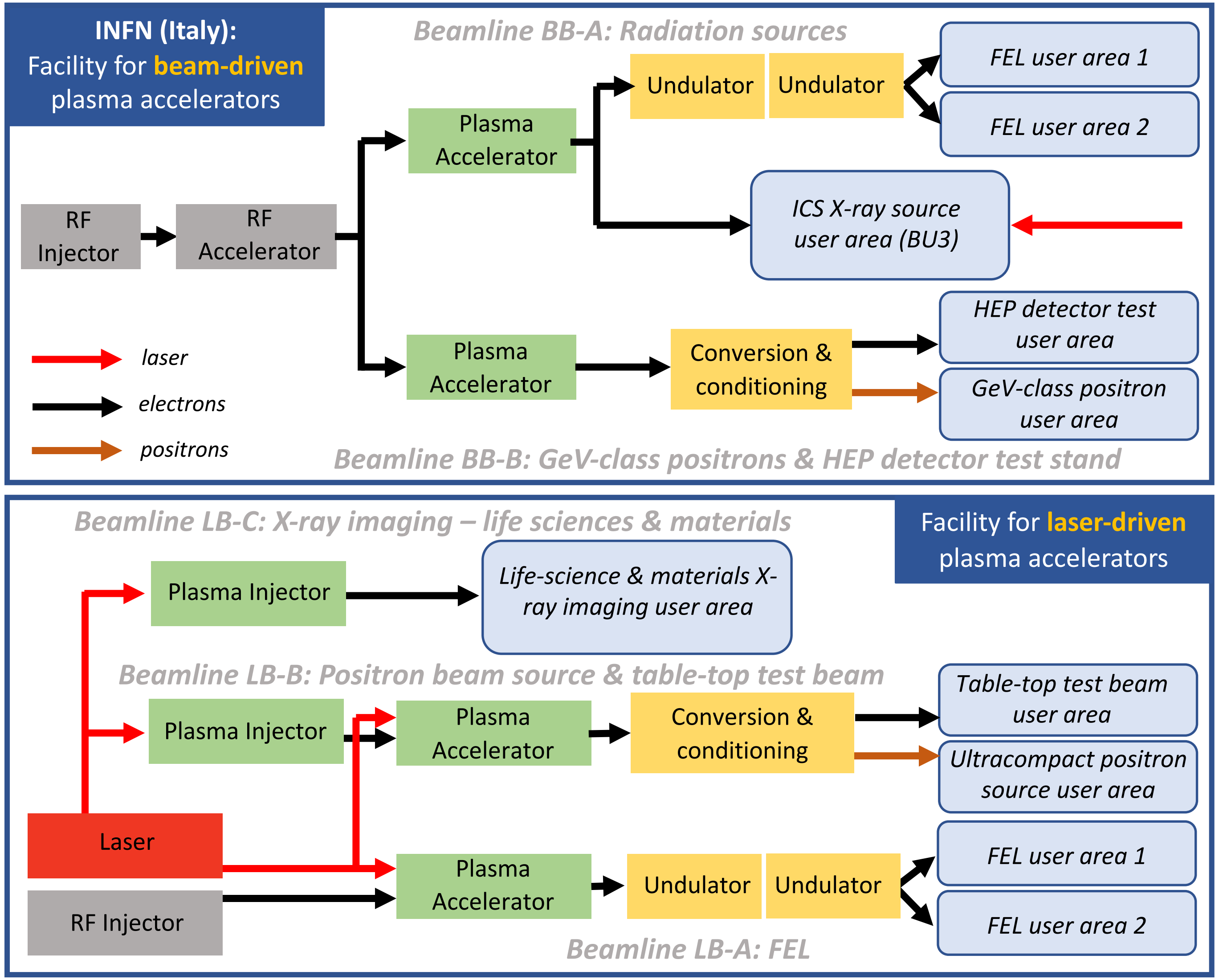
	Laser-driven	Beam-driven
Phase 1	✓ FEL beamline to 1 GeV + user area 1 ✓ Ultracompact positron source beamline + positron user area	✓ FEL beamline to 1 GeV + user area 1 ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ X-ray imaging beamline + user area ✓ Table-top test beams user area ✓ FEL user area 2 ✓ FEL to 5 GeV	✓ ICS source beamline + user area ✓ HEP detector tests user area ✓ FEL user area 2 ✓ FEL to 5 GeV
Phase 3	✓ High-field physics beamline / user area ✓ Other future developments	✓ Medical imaging beamline / user area ✓ Other future developments



Phased Implementation of Construction Sites

Horizon 2020

	Laser-driven	Beam-driven
Phase 1	✓ FEL beamline to 1 GeV + user area 1 ✓ Ultracompact positron source beamline + positron user area	✓ FEL beamline to 1 GeV + user area 1 ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ X-ray imaging beamline + user area ✓ Table-top test beams user area ✓ FEL user area 2 ✓ FEL to 5 GeV	✓ ICS source beamline + user area ✓ HEP detector tests user area ✓ FEL user area 2 ✓ FEL to 5 GeV
Phase 3	✓ High-field physics beamline / user area ✓ Other future developments	✓ Medical imaging beamline / user area ✓ Other future developments



INFN (Italy):
Facility for **beam-driven** plasma accelerators

Beamline BB-A: Radiation sources

RF Injector
RF Accelerator
Plasma Accelerator
Undulator
Undulator
FEL user area 1
FEL user area 2
ICS X-ray source user area (BU3)
Plasma Accelerator
Conversion & conditioning
HEP detector test user area
GeV-class positron user area

laser
electrons
positrons

Beamline BB-B: GeV-class positrons & HEP detector test stand

Beamline LB-C: X-ray imaging – life sciences & materials

Facility for **laser-driven** plasma accelerators

Plasma Injector
Life-science & materials X-ray imaging user area

Beamline LB-B: Positron beam source & table-top test beam

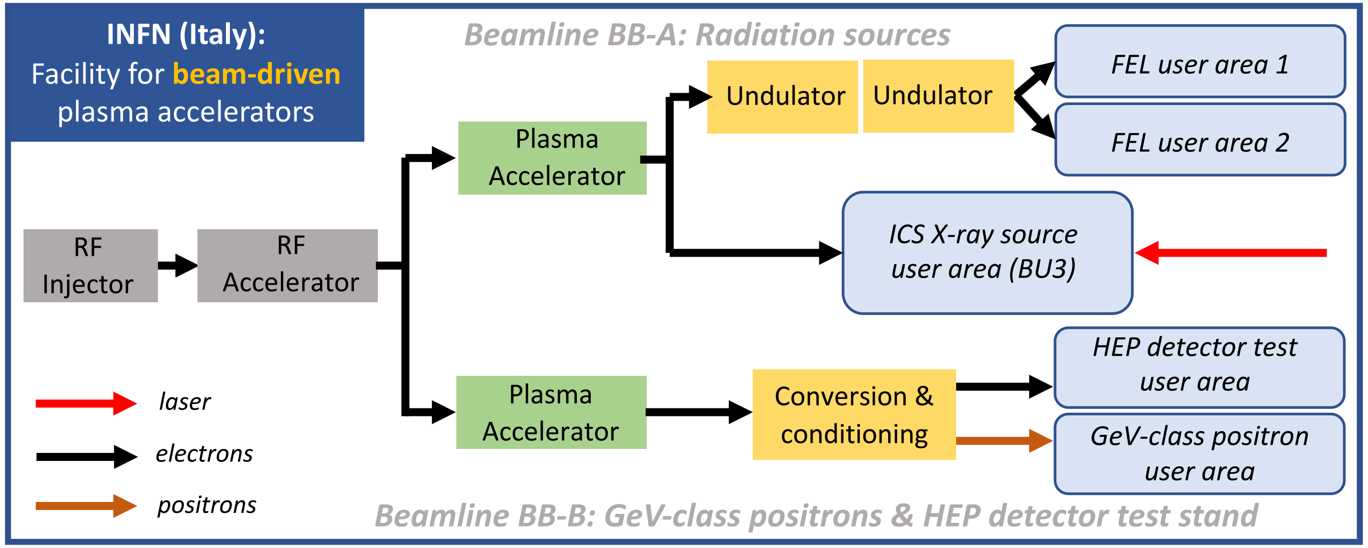
Plasma Injector
Plasma Accelerator
Conversion & conditioning
Table-top test beam user area
Ultracompact positron source user area
Laser
RF Injector
Plasma Accelerator
Undulator
Undulator
FEL user area 1
FEL user area 2

Beamline LB-A: FEL

Phased Implementation of Construction Sites

Horizon 2020

	Laser-driven	Beam-driven
Phase 1	✓ FEL beamline to 1 GeV + user area 1 ✓ Ultracompact positron source beamline + positron user area	✓ FEL beamline to 1 GeV + user area 1 ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ X-ray imaging beamline + user area ✓ Table-top test beams user area ✓ FEL user area 2 ✓ FEL to 5 GeV	✓ ICS source beamline + user area ✓ HEP detector tests user area ✓ FEL user area 2 ✓ FEL to 5 GeV
Phase 3	✓ High-field physics beamline / user area ✓ Other future developments	✓ Medical imaging beamline / user area ✓ Other future developments



INFN (Italy):
Facility for **beam-driven** plasma accelerators

Beamline BB-A: Radiation sources

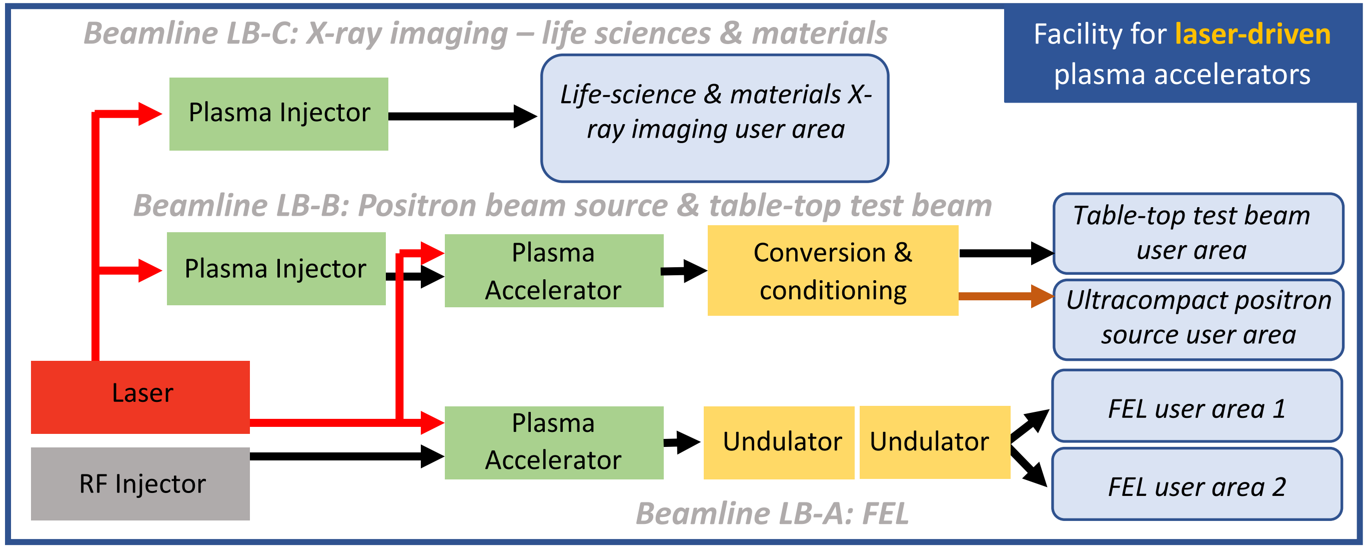
RF Injector → RF Accelerator → Plasma Accelerator → Undulator → Undulator → *FEL user area 1* / *FEL user area 2*

Plasma Accelerator → *ICS X-ray source user area (BU3)* ← laser

RF Accelerator → Plasma Accelerator → Conversion & conditioning → *HEP detector test user area* / *GeV-class positron user area*

Beamline BB-B: GeV-class positrons & HEP detector test stand

Legend: *laser*, *electrons*, *positrons*



Facility for **laser-driven** plasma accelerators

Beamline LB-C: X-ray imaging – life sciences & materials

Laser → Plasma Injector → *Life-science & materials X-ray imaging user area*

Beamline LB-B: Positron beam source & table-top test beam

Laser → Plasma Injector → Plasma Accelerator → Conversion & conditioning → *Table-top test beam user area* / *Ultracompact positron source user area*

Laser / RF Injector → Plasma Accelerator → Undulator → Undulator → *FEL user area 1* / *FEL user area 2*

Beamline LB-A: FEL

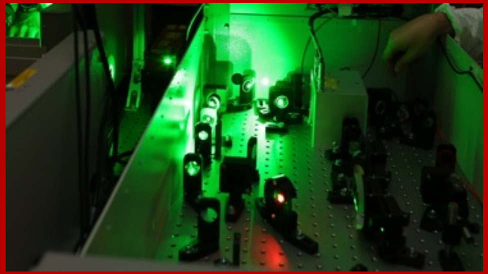
Future development paths & potential long-term science program activities

Horizon 2020

1. High power laser technology

1.1 High repetition rate

1.2 High average power



2. Accelerator technology

2.1 Staging towards high energies

2.2 Compact diagnostics

2.3 Hybrid plasma acceleration & other novel injection concepts

2.4 Beam control & quality

2.5 Ultrashort beams

3. Plasma-based FEL

3.1 Higher photon flux

3.2 Lower wavelength

3.3 Compact beamline components (undulators, magnets, etc.)

3.4 Ultrashort beams

3.5 Seeded FEL

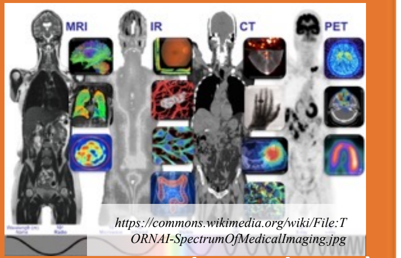
4. Plasma accelerator applications: method development & application

4.1 Medical imaging

4.2 High-energy physics detectors

4.3 Material analysis (cargo scanning, structural analysis)

4.4 Positron generation and acceleration

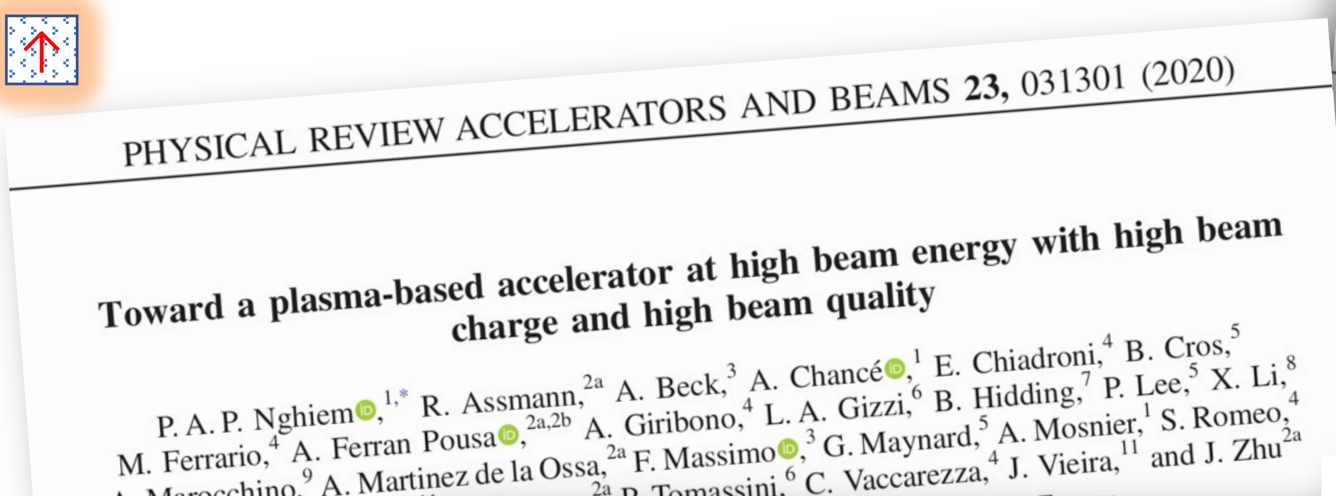


https://commons.wikimedia.org/wiki/File:TORNAI-SpectrumOfMedicalImaging.jpg

Outline

- The Plasma Accelerator Context
- The EuPRAXIA Objective
- ESFRI and EuPRAXIA
- EuPRAXIA as a User Facility
- EuPRAXIA Implementation
- **EuPRAXIA Innovation**
- EuPRAXIA ESFRI Features
- Towards Particle Physics
- Conclusion

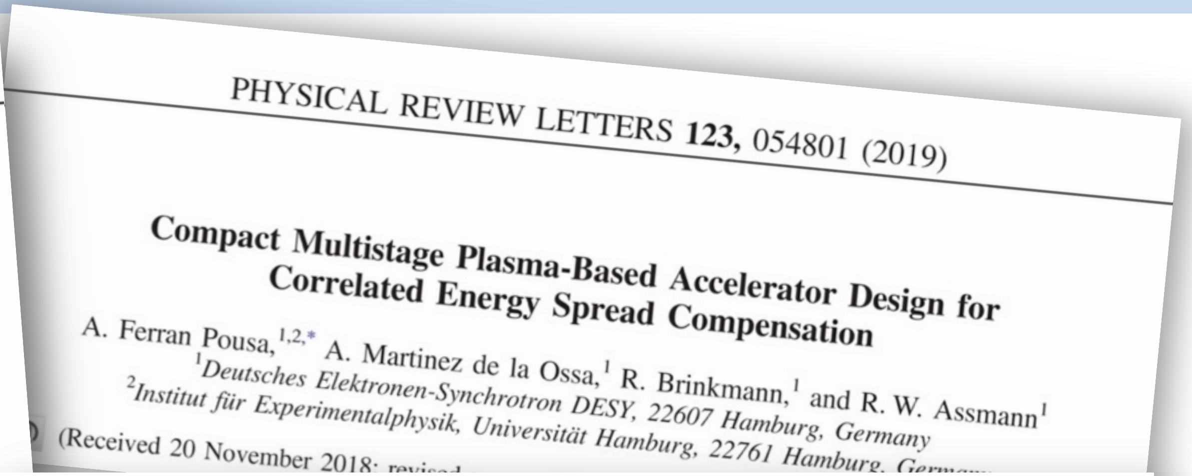
Examples of EuPRAXIA Ideas and Innovation



PHYSICAL REVIEW ACCELERATORS AND BEAMS **23**, 031301 (2020)

Toward a plasma-based accelerator at high beam energy with high beam charge and high beam quality

P. A. P. Nghiem,[1,*] R. Assmann,[2a] A. Beck,[3] A. Chancé,[1] E. Chiadroni,[4] B. Cros,[5]
M. Ferrario,[4] A. Ferran Pousa,[2a,2b] A. Giribono,[4] L. A. Gizzi,[6] B. Hidding,[7] P. Lee,[5] X. Li,[8]
A. Marocchino,[9] A. Martinez de la Ossa,[2a] F. Massimo,[3] G. Maynard,[5] A. Mosnier,[1] S. Romeo,[4]
A. R. Rossi,[10] T. Silva P. Tomassini,[6] C. Vaccarezza,[4] J. Vieira,[11] and J. Zhu[2a]
[1]CEA, IF

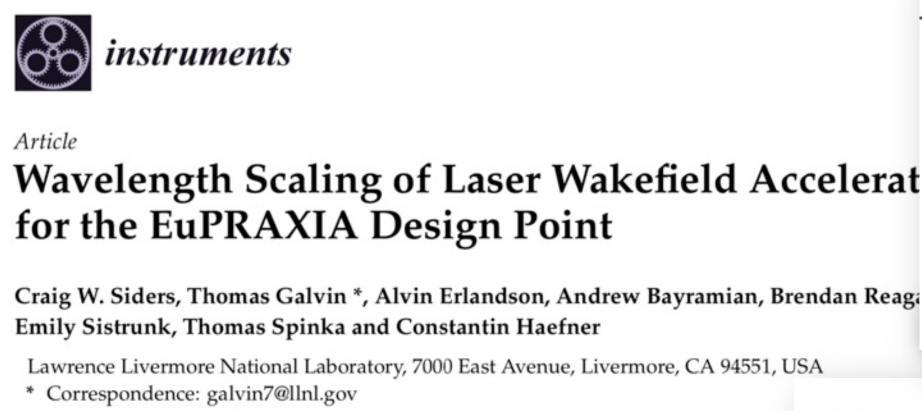


PHYSICAL REVIEW LETTERS **123**, 054801 (2019)

Compact Multistage Plasma-Based Accelerator Design for Correlated Energy Spread Compensation

A. Ferran Pousa,[1,2,*] A. Martinez de la Ossa,[1] R. Brinkmann,[1] and R. W. Assmann[1]
[1]*Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany*
[2]*Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germ*

(Received 20 November 2018;



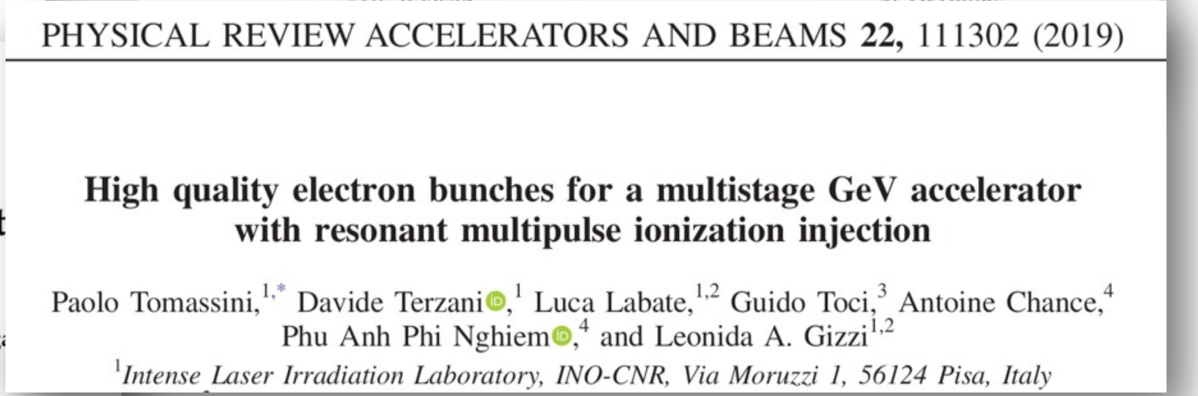
instruments

Article

Wavelength Scaling of Laser Wakefield Accelerat for the EuPRAXIA Design Point

Craig W. Siders, Thomas Galvin *, Alvin Erlandson, Andrew Bayramian, Brendan Reaga Emily Sistrunk, Thomas Spinka and Constantin Haefner

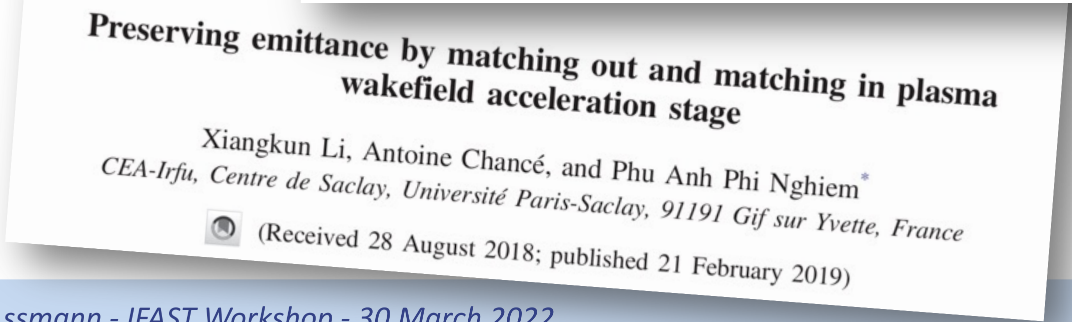
Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94551, USA
* Correspondence: galvin7@llnl.gov



PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 111302 (2019)

High quality electron bunches for a multistage GeV accelerator with resonant multipulse ionization injection

Paolo Tomassini,[1,*] Davide Terzani,[1] Luca Labate,[1,2] Guido Toci,[3] Antoine Chance,[4]
Phu Anh Phi Nghiem,[4] and Leonida A. Gizzi[1,2]
[1]*Intense Laser Irradiation Laboratory, INO-CNR, Via Moruzzi 1, 56124 Pisa, Italy*

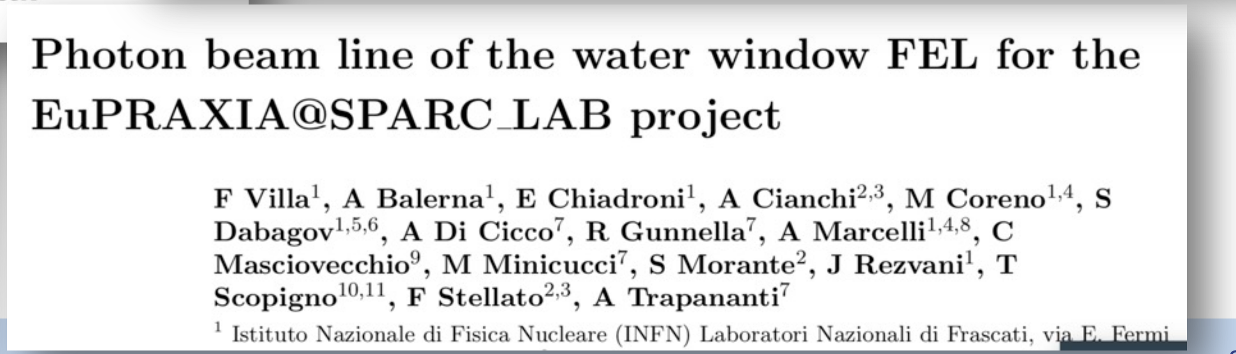


PHYSICAL REVI

Preserving emittance by matching out and matching in plasma wakefield acceleration stage

Xiangkun Li, Antoine Chancé, and Phu Anh Phi Nghiem[*]
CEA-Irfu, Centre de Saclay, Université Paris-Saclay, 91191 Gif sur Yvette, France

(Received 28 August 2018; published 21 February 2019)



Photon beam line of the water window FEL for the EuPRAXIA@SPARC_LAB project

F Villa[1], A Balerna[1], E Chiadroni[1], A Cianchi[2,3], M Coreno[1,4], S Dabagov[1,5,6], A Di Cicco[7], R Gunnella[7], A Marcelli[1,4,8], C Masciovecchio[9], M Minicucci[7], S Morante[2], J Rezvani[1], T Scopigno[10,11], F Stellato[2,3], A Trapananti[7]
[1] Istituto Nazionale di Fisica Nucleare (INFN) Laboratori Nazionali di Frascati, via E. Fermi

Is it really useful beam?

Remarkable progress – faster than planned for:

It can drive an FEL lasing process – sufficient coherency!

Nature July 2021

The international journal of science / 22 July 2021

nature

COMPACT SOURCE

Plasma-based acceleration paves way to smaller free-electron lasers

Firearm focus
Fresh funding boosts US studies on gun violence

Detecting emissions
How to verify compliance with Paris and Montreal treaties

Flow charts
How fluid dynamics help a deep-sea sponge feed and reproduce

W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).

Article | Published: 21 July 2021

Free-electron lasing at 27 nanometres based on a laser wakefield accelerator

Wentao Wang, Ke Feng, Lintong Ke, Changhai Yu, Yi Xu, Rong Qi, Yu Chen, Zhiyong Qin, Zhijun Zhang, Ming Fang, Jiaqi Liu, Kangnan Jiang, Hao Wang, Cheng Wang, Xiaojun Yang, Fenxiang Wu, Yuxin Leng, Jiansheng Liu, Ruxin Li & Zhizhan Xu

Nature **595**, 516–520 (2021) | Cite this article

Recent ground-breaking result in China

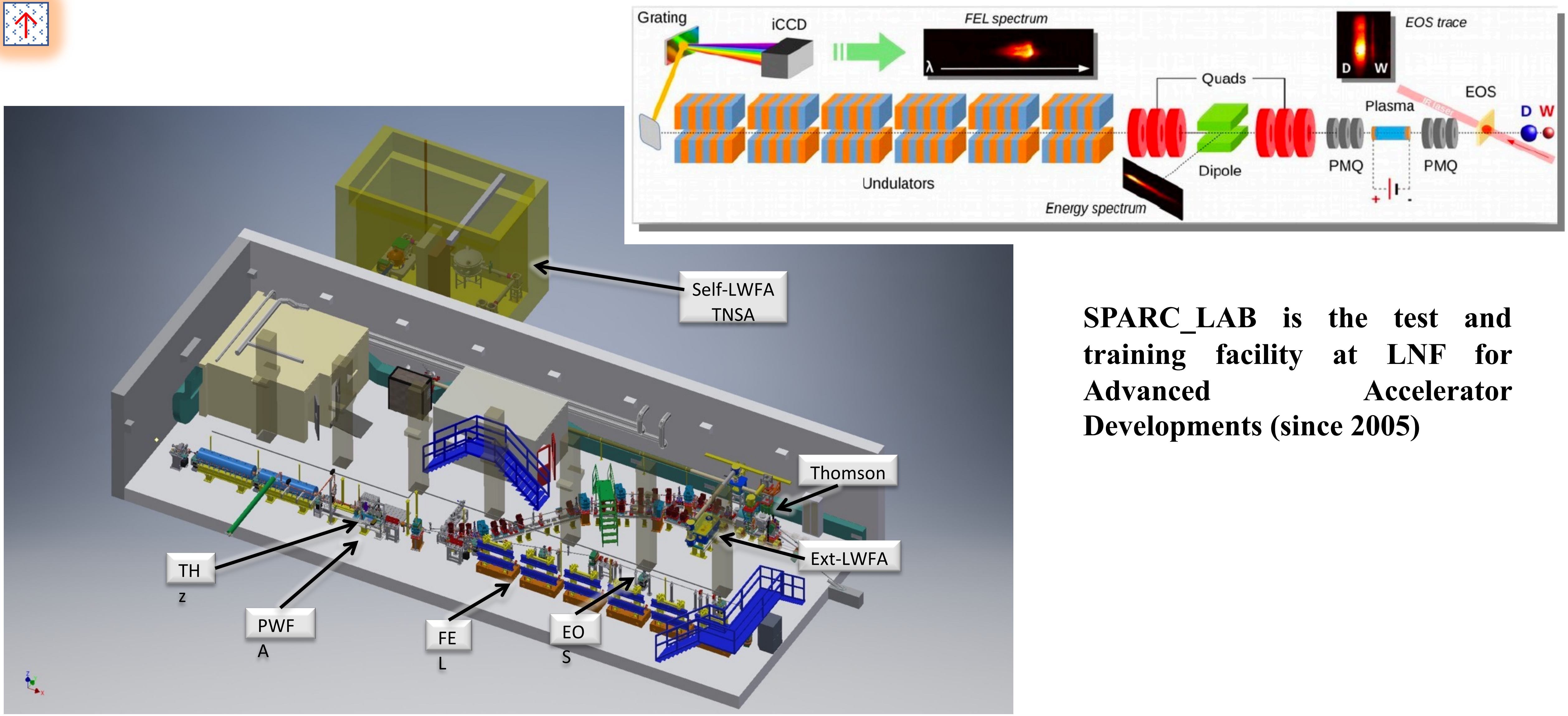
500 MeV electron beam from a laser wakefield accelerator

FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)

Nature Coming Soon (Accepted)

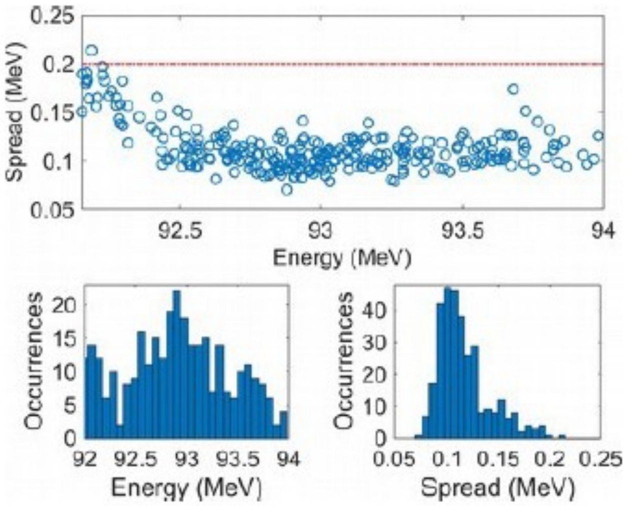
First SASE-FEL Lasing at SPARC_LAB in a beam-driven plasma accelerator

SPARC_LAB at Frascati



SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)

Assisted Beam Loading Energy Spread Compensation



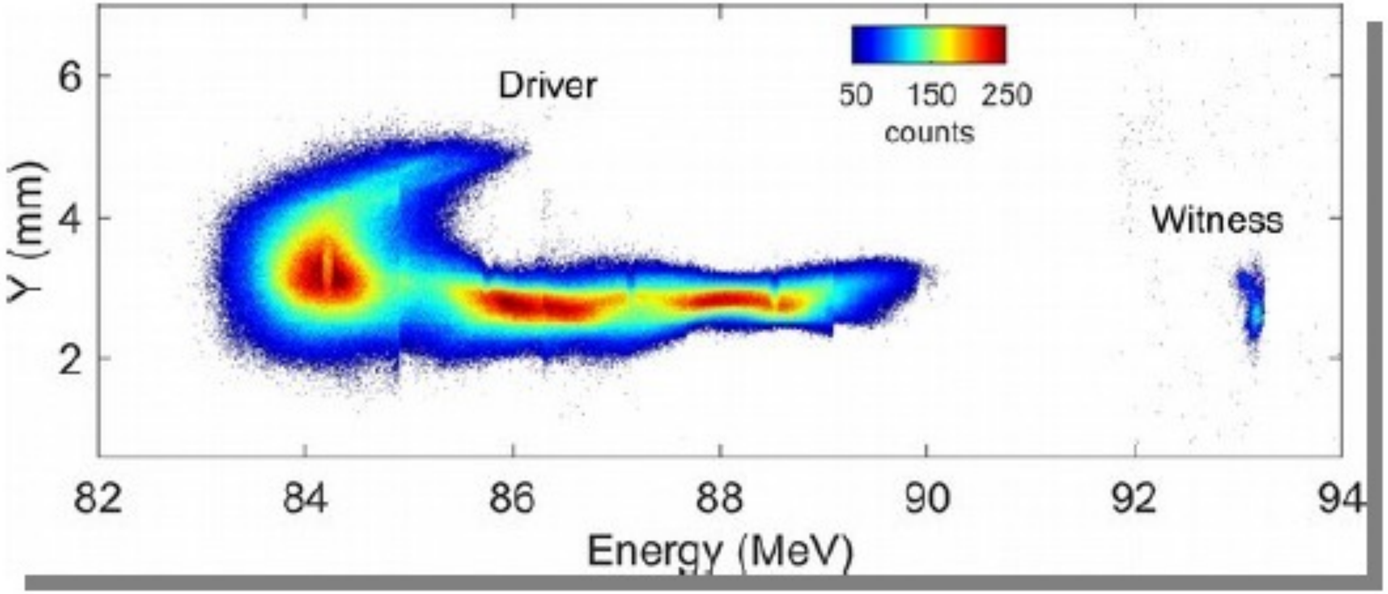
Pompili, R., et al. "Energy spread minimization in a beam-driven plasma wakefield accelerator." Nature Physics (2020): 1-5.

Achieved 4 MeV acceleration in 3 cm plasma with 200 pC driver

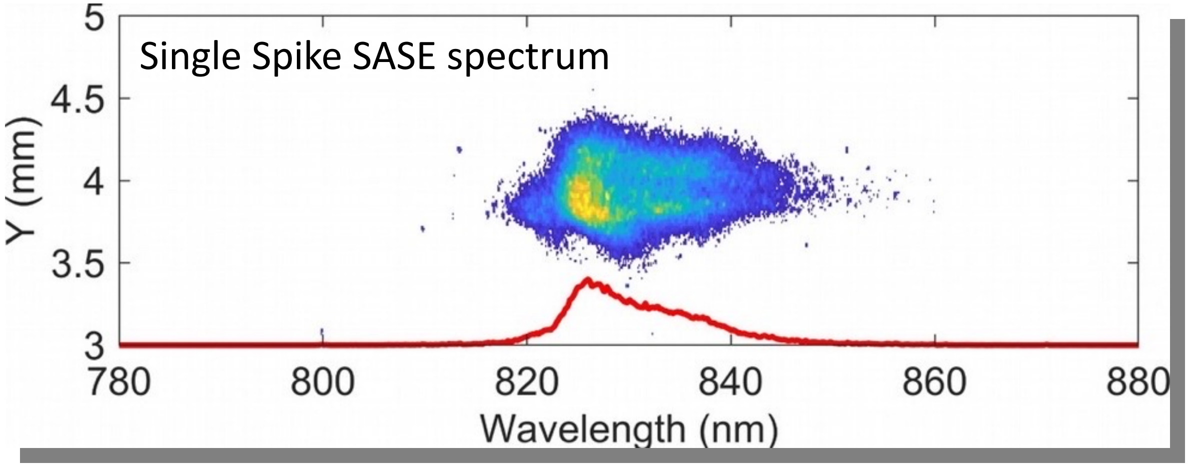
- *~133 MV/m accelerating gradient*
- *$2x10^{15}$ cm^{-3} plasma density*

[illegible] demonstration of energy spread compensation during acceleration

- *Energy spread reduced from 0.2% to 0.12%*
- *99.5% energy stability*

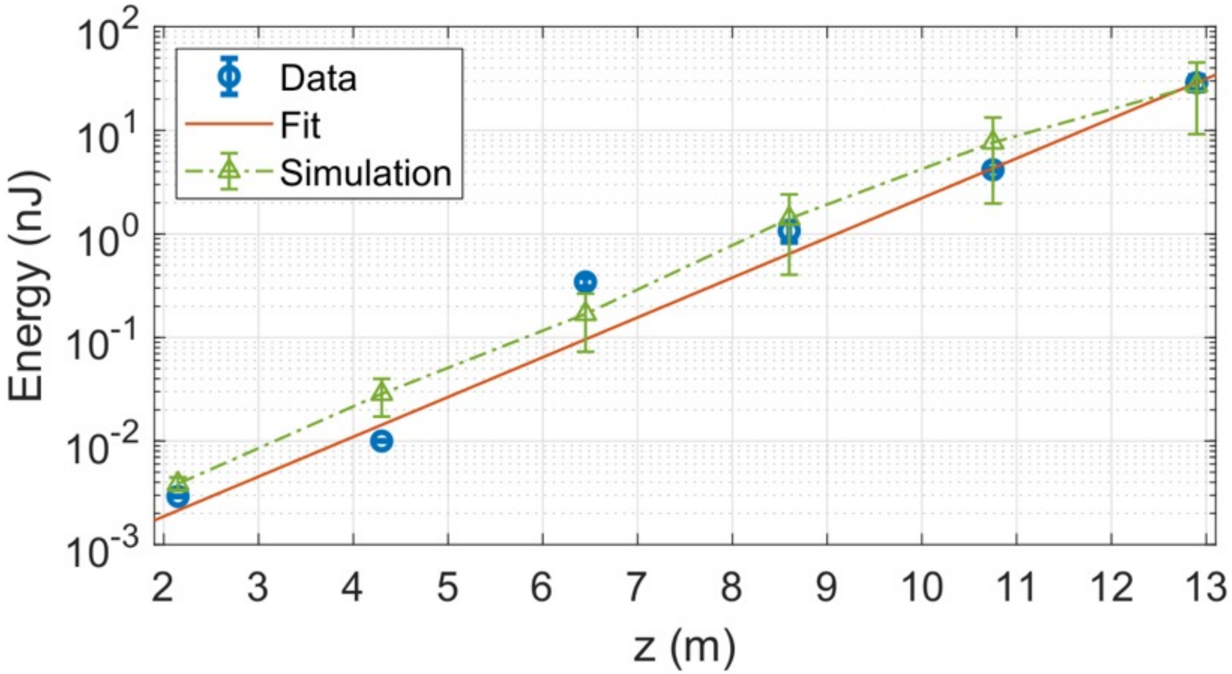


Nature Coming Soon (Accepted)

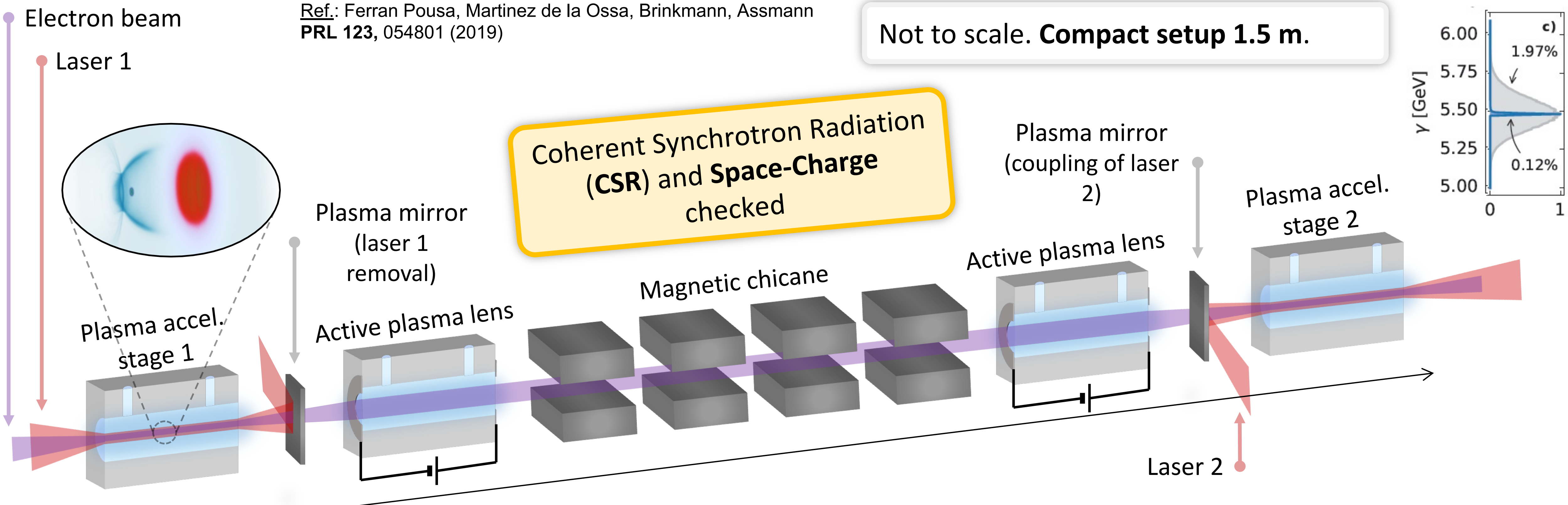


First SASE-FEL Lasing at SPARC_LAB in a beam-driven plasma accelerator

FEL Energy gain along the undulators:



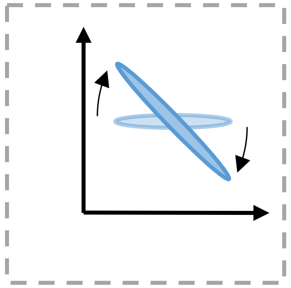
Solving Energy Spread (Touschek Prize 2020)



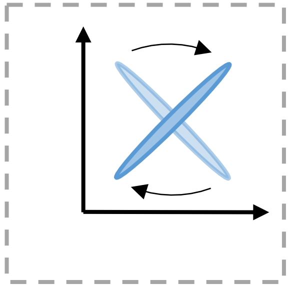
Ref.: Ferran Pousa, Martinez de la Ossa, Brinkmann, Assmann
PRL 123, 054801 (2019)

Not to scale. **Compact setup 1.5 m.**

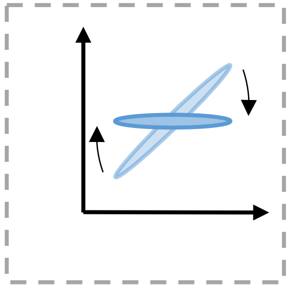
Coherent Synchrotron Radiation (**CSR**) and **Space-Charge** checked



Accelerating in a plasma stage and...



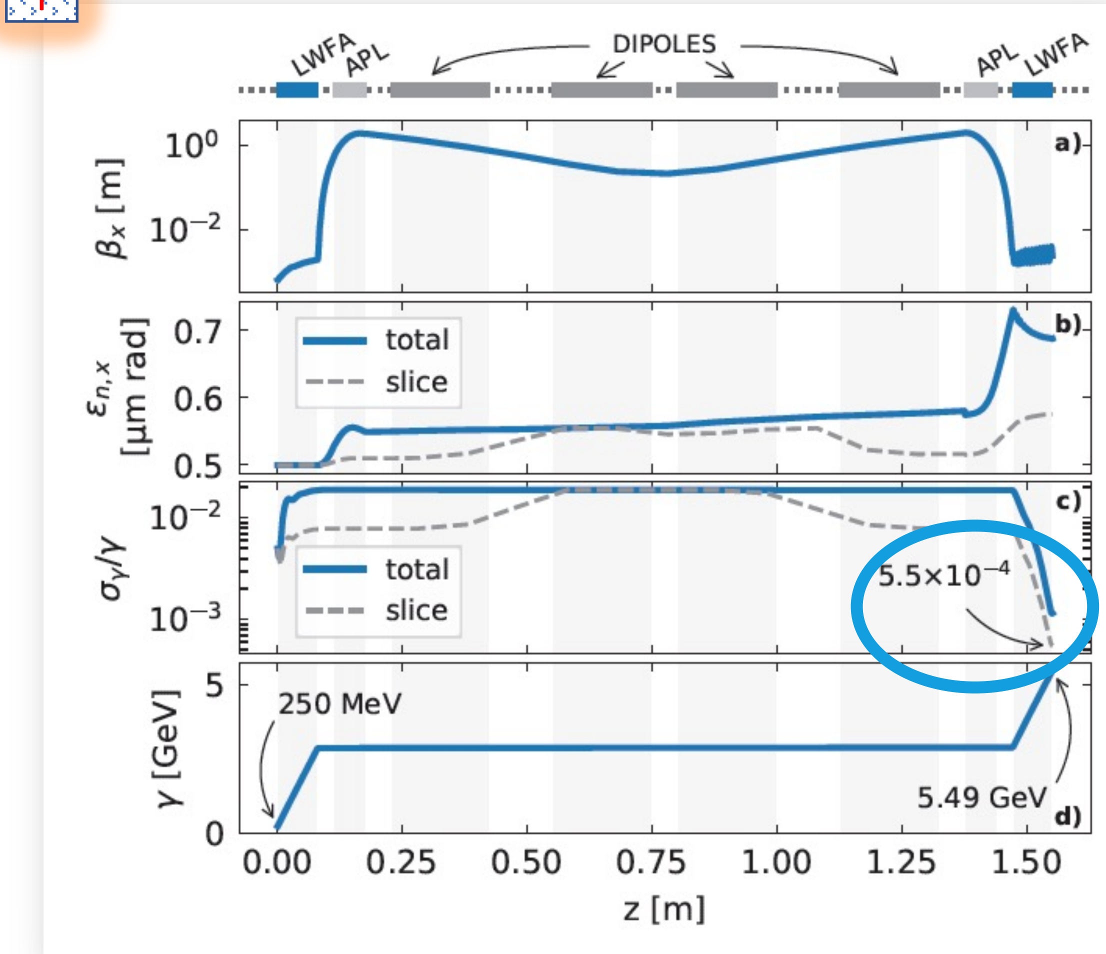
... flipping phase space in the middle before second plasma stage

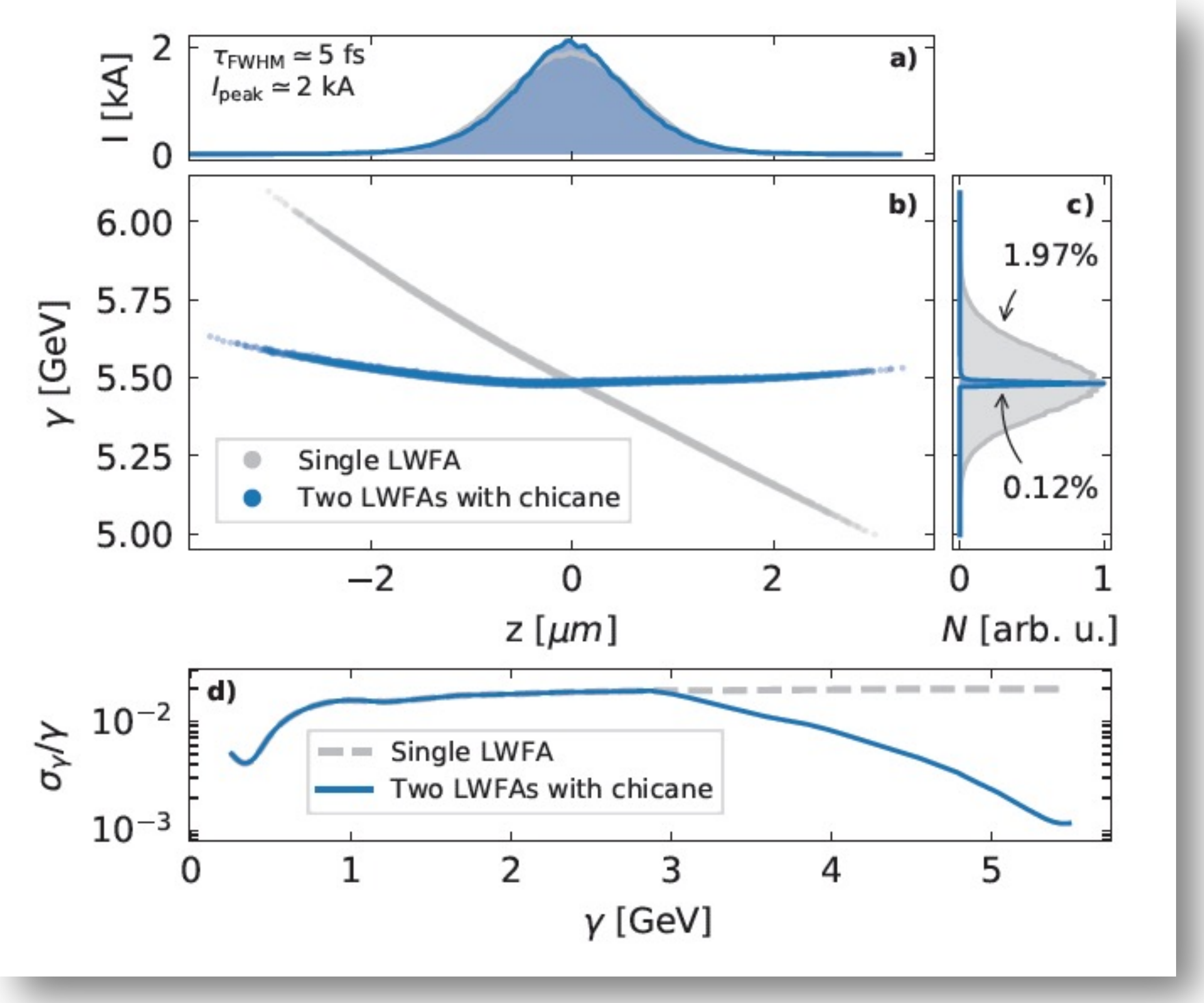


Low Energy Spread with 2 Stages

Horizon 2020

Ref.: Ferran Pousa, Martinez de la Ossa, Brinkmann, Assmann. **PRL 123,** 054801 (2019)

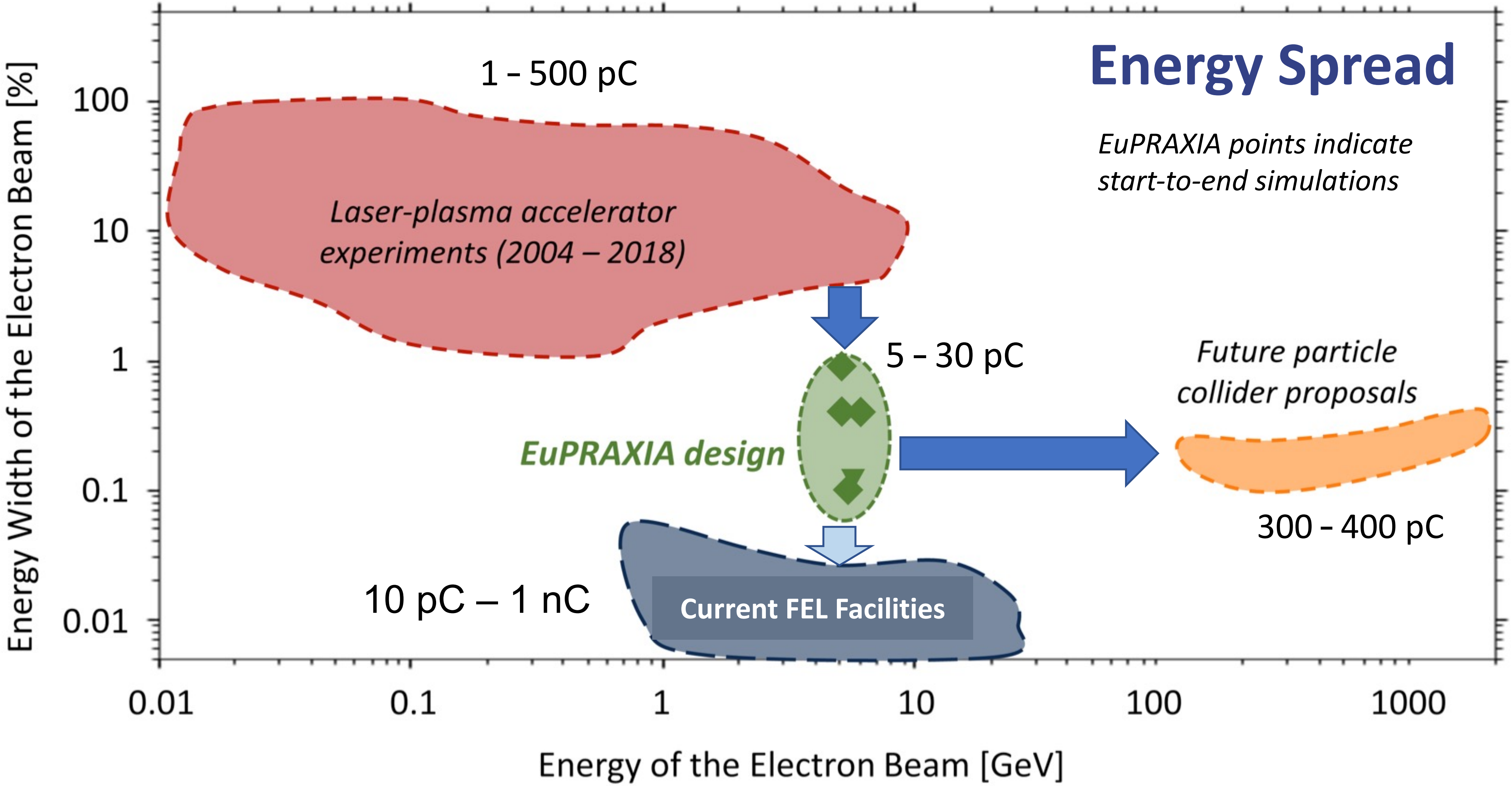




Much better than a single stage performance

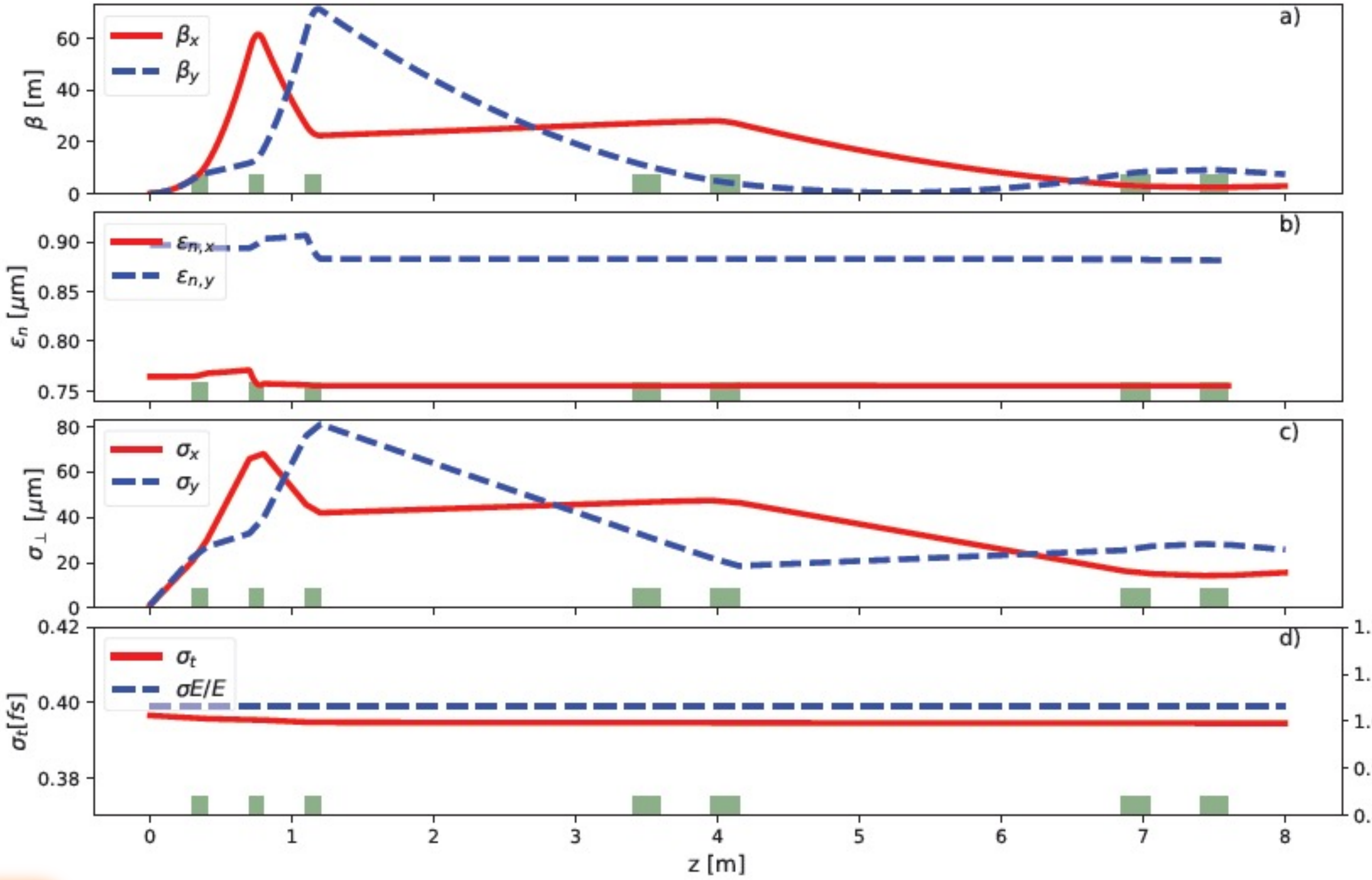
Prize to pay: control beam dynamics in the chicane → micro-bunch instability to be controlled (known from big accelerators)

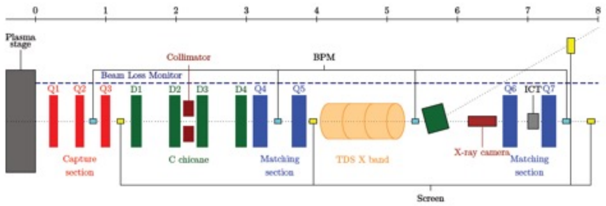
Solving Energy Spread



EuPRAXIA points indicate start-to-end simulations

Beam Transport Design





- Here: high energy **beam transport over 8 meters**
- Preserved beam quality is achieved in the design
- Space has important benefits

A. Chance et al

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Solve external timing for laser-driven plasma acc.

External injection into a laser-driven plasma accelerator with sub-femtosecond timing jitter

A Ferran Pousa[1,2], R Assmann[1], R Brinkmann[1] and A Martinez de la Ossa[1,2]

[1] DESY, 22607 Hamburg, Germany
[2] Universität Hamburg, 22761 Hamburg, Germany

E-mail: `angel.ferran.pousa@desy.de`

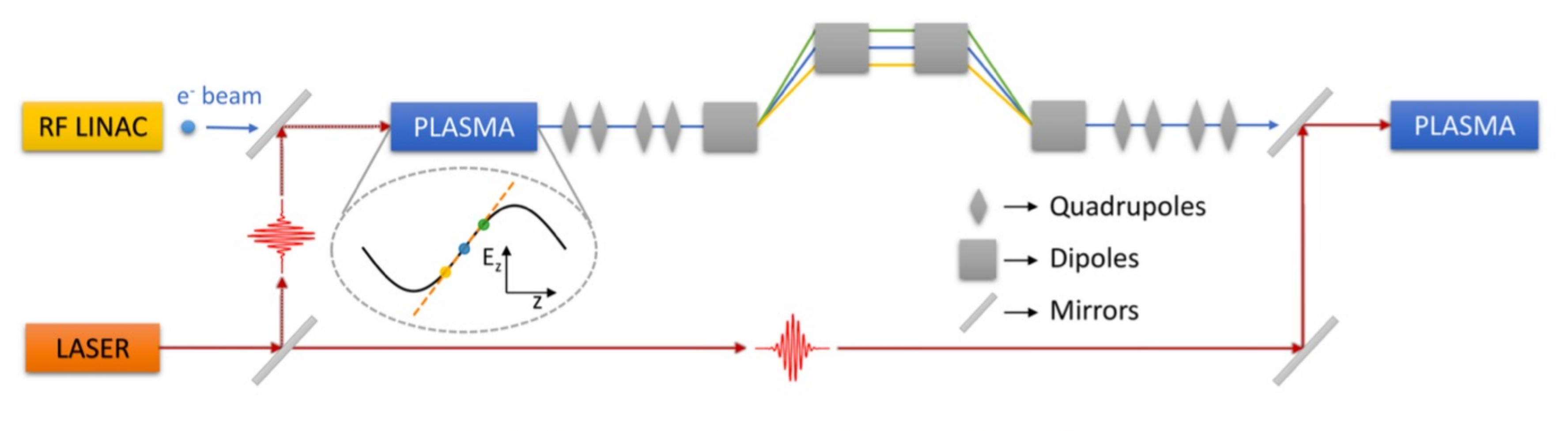


Figure 1. Schematic view of the synchronizing stage.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Spin Polarization | Hybrid Plasma Accelerators

- e+e- colliders and physics reach enhanced by spin polarized beams
- International Partners: Germany, Greece, China, and USA → facilities involved at FZJ, Shanghai, ...

Snowmass 2021 – Letter of Interest Aug/31/2020

Polarized targets for laser-plasma applications

M. Büscher[1,2], A. Hützen[1,2], J. Böker[3], R.W. Engels[3], R. Gebel[3], A. Lehrach[3,4], P. Gibbon[5], A. Pukhov[6], R.W. Aßmann[7], T.P. Rakitzis[8,9], L. Ji[10,11], T. Schenkel[12], X. Wei[13]

[1] Peter Grünberg Institut (PGI-6), Forschungszentrum Jülich, 52425 Jülich, Germany
[2] Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[3] Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany
[4] JARA-FAME Forschungszentrum Jülich and RWTH Aachen University, 52056 Aachen, Germany
[5] Institute for Advanced Simulation, Jülich Supercomputing Centre, Forschungszentrum Jülich, 52425 Jülich, Germany
[6] Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[7] DESY, Notkestraße 85, 22607, Hamburg, Germany
[8] Department of Physics, University of Crete, 71003 Heraklion-Crete, Greece
[9] Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, 71110 Heraklion-Crete, Greece
[10] State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Shanghai 201800, China
[11] CAS Center for Excellence in Ultra-intense Laser Science, Shanghai 201800, China
[12] Accelerator Technology and Applied Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[13] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

- Use a laser-generated electron beam for driving plasma wakefields in a second stage → HQ electron beam from ultra-compact setup
- Several facilities involved at HZDR, Strathclyde, ...

Hybrid LWFA-PWFA staging (LPWFA) as a beam energy and brightness transformer

Arie Irman
Helmholtz-Zentrum Dresden– Rossendorf

Sebastien Corde[1], Andreas Döpp[2], Bernhard Hidding[3], Stefan Karsch[2], Alberto Martinez de la Ossa[5], Ulrich Schramm[6] - *for hybrid LWFA-PWFA collaboration*

[1] LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institute Polytechnique de Paris, 91762 Palaiseau, France
[2] Ludwig-Maximilians-Universität München, Am Coulombwall 1, 85748 Garching, Germany
[3] The Cockcroft Institute, Keckwick Lane, Daresbury, Cheshire WA4 4AD, United Kingdom
[4] University of Strathclyde, 107 Rottenrow, Glasgow G4 0NG, United Kingdom
[5] Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany
[6] Helmholtz-Zentrum Dresden – Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany

SnowMass2021- AF6 Oral Session 24 September 2010

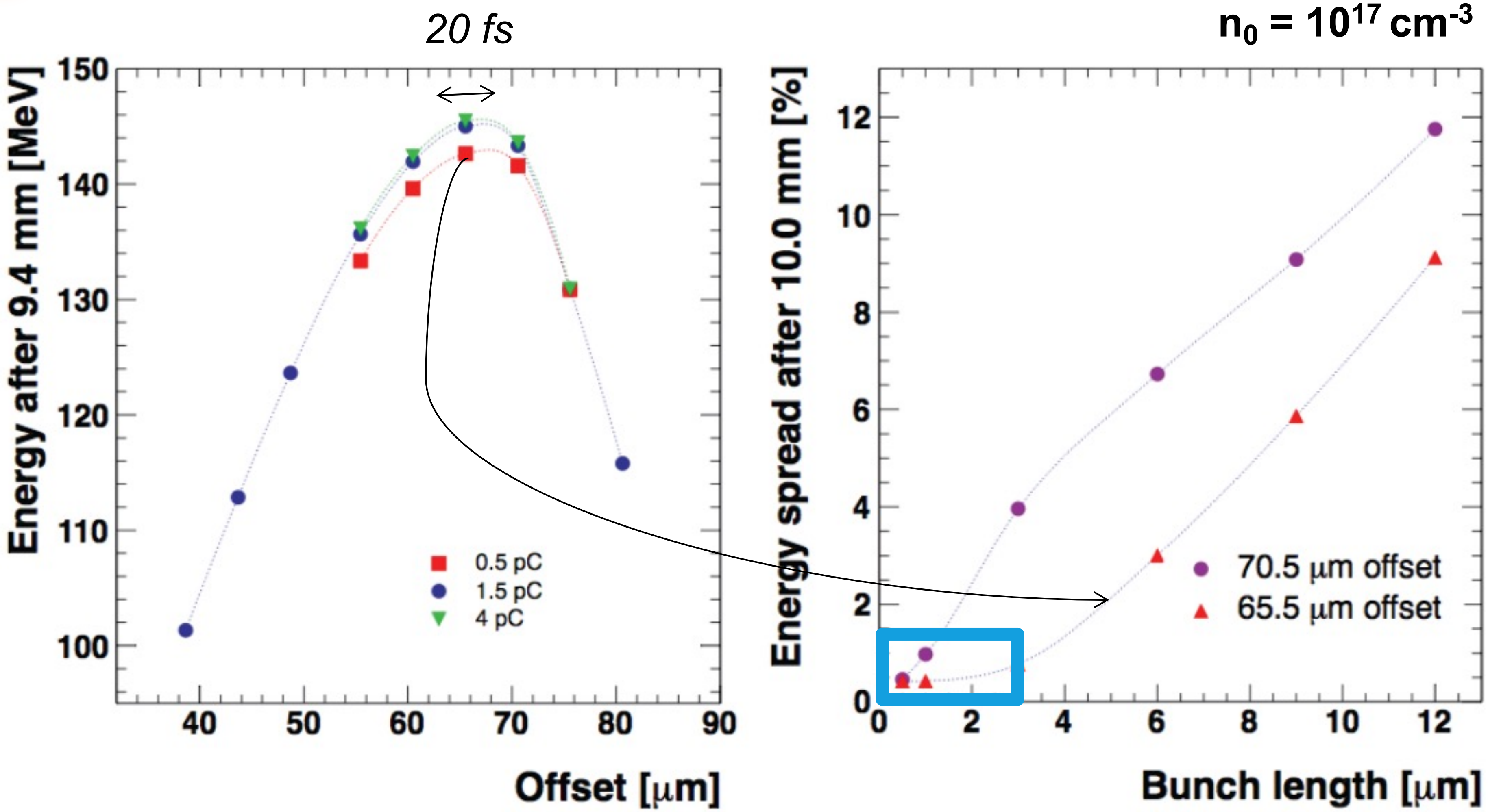
MT ACCELERATOR RESEARCH & DEVELOPMENT

Arie Irman • a.irman@hzdr.de
Institute of Radiation Physics
Member of the Helmholtz Association
Page 1

Limits in Energy Spread

Gedankenexperiment – Zero Bunch Length

Infinitesimally short bunch will not see any slope of accelerating voltage



Here, longitudinal field independent of radial position

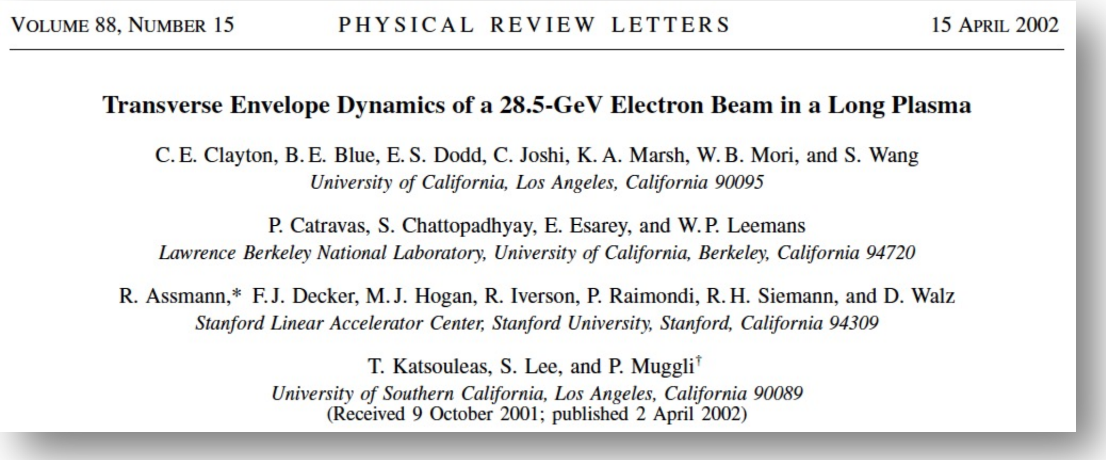
Zero bunch length → all particles at same longitudinal coord. and see the same acceleration.

Why does energy spread not go to zero for zero bunch length?

Limits in Energy Spread

Strong plasma focusing: Betatron motion

- A plasma has a very strong focusing field in both planes.
- Focusing strength and phase advance depends on plasma density.
- Experiment with a beam-driven plasma at SLAC in 2001: Send an electron beam into a plasma and measure beam sizes at exit point.



VOLUME 88, NUMBER 15 PHYSICAL REVIEW LETTERS 15 APRIL 2002

Transverse Envelope Dynamics of a 28.5-GeV Electron Beam in a Long Plasma

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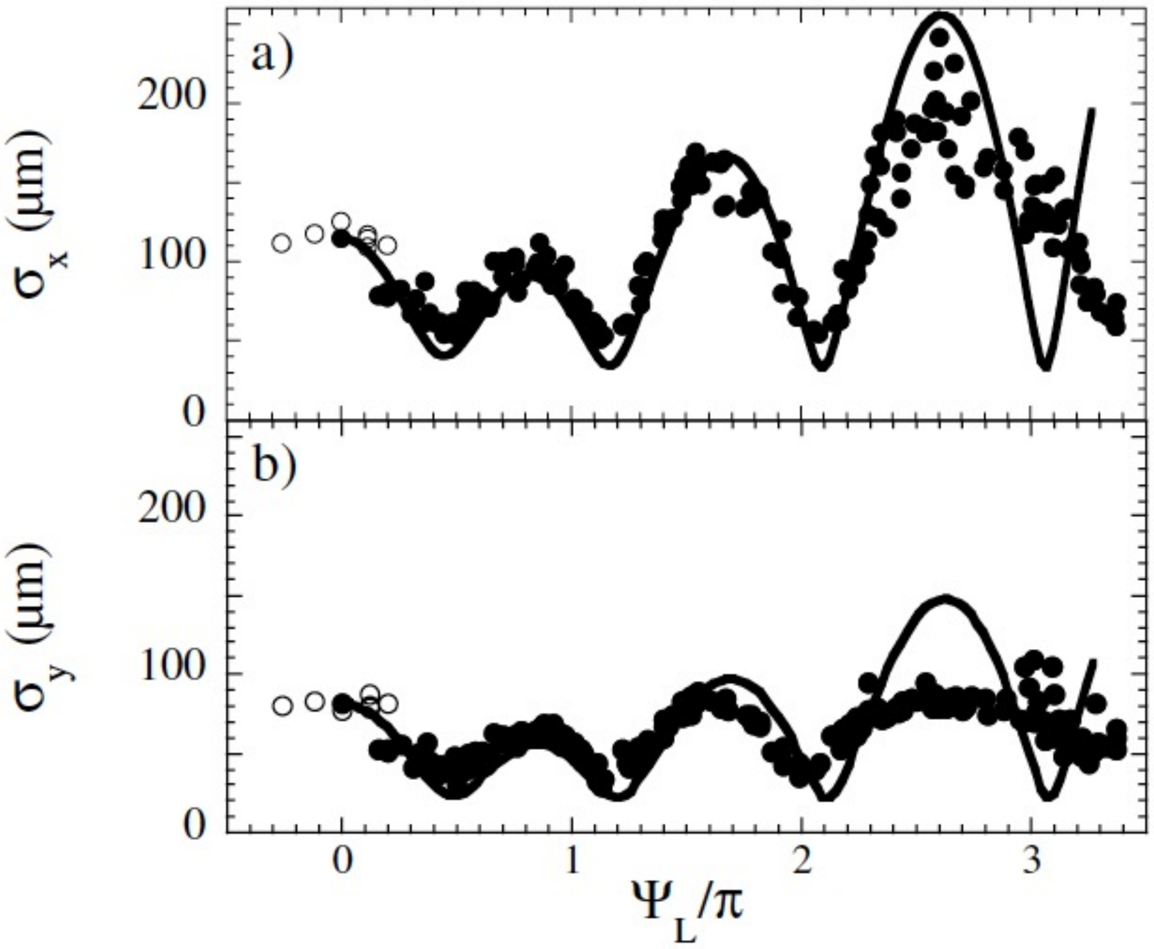
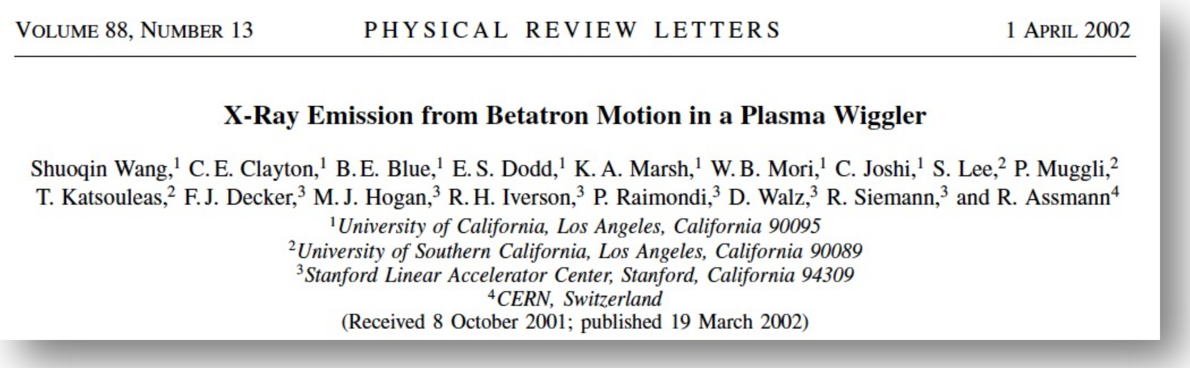


Limits in Energy Spread

Strong plasma focusing: Betatron motion and X rays

- If an electron beam is injected mis-matched into a plasma, we expect strong beta mismatch oscillations of the beam size.
- The oscillating electrons should radiate X rays.
- This was seen in a SLAC experiment in 2001.
- Plasma acts as undulator!



VOLUME 88, NUMBER 13 PHYSICAL REVIEW LETTERS 1 APRIL 2002

X-Ray Emission from Betatron Motion in a Plasma Wiggler

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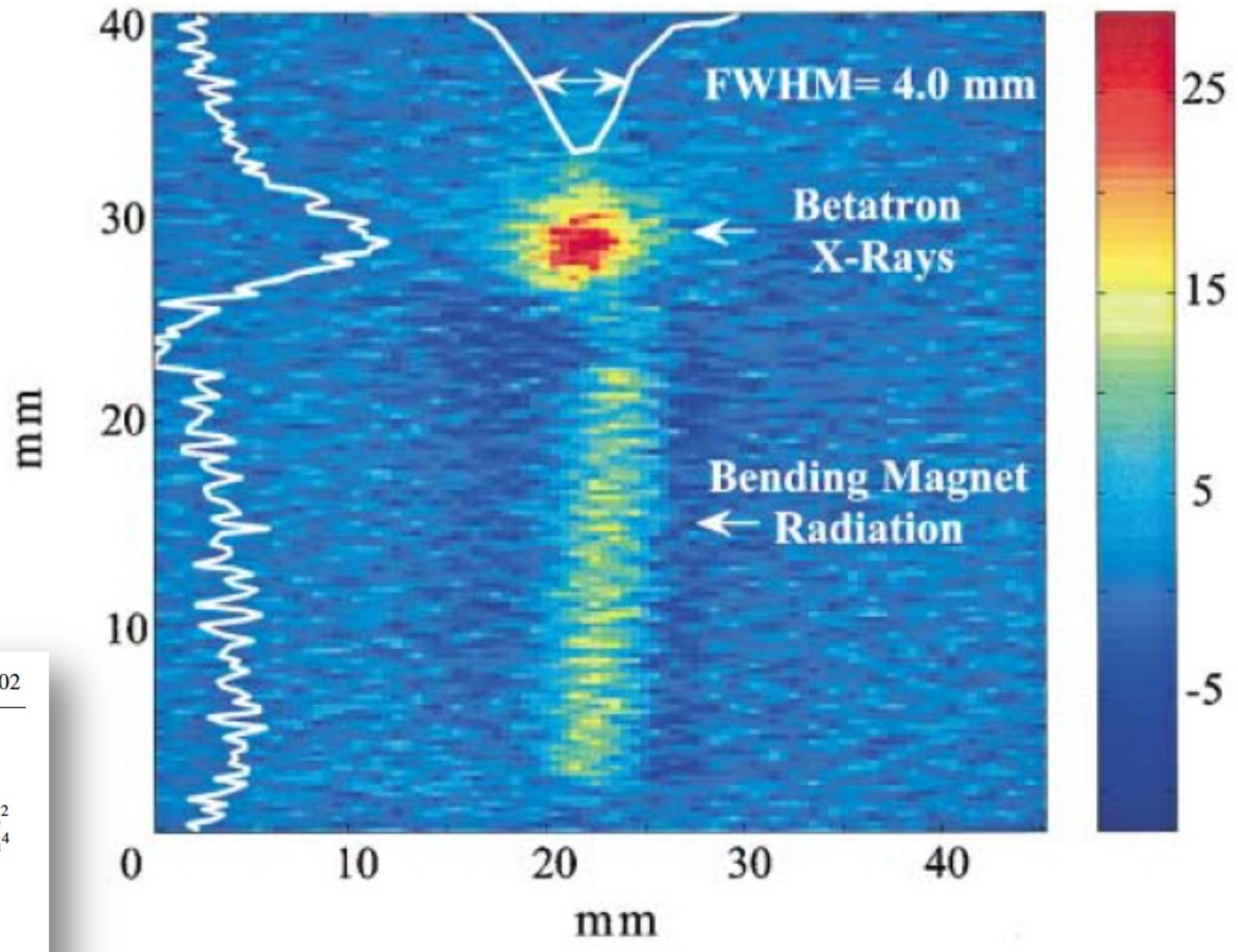
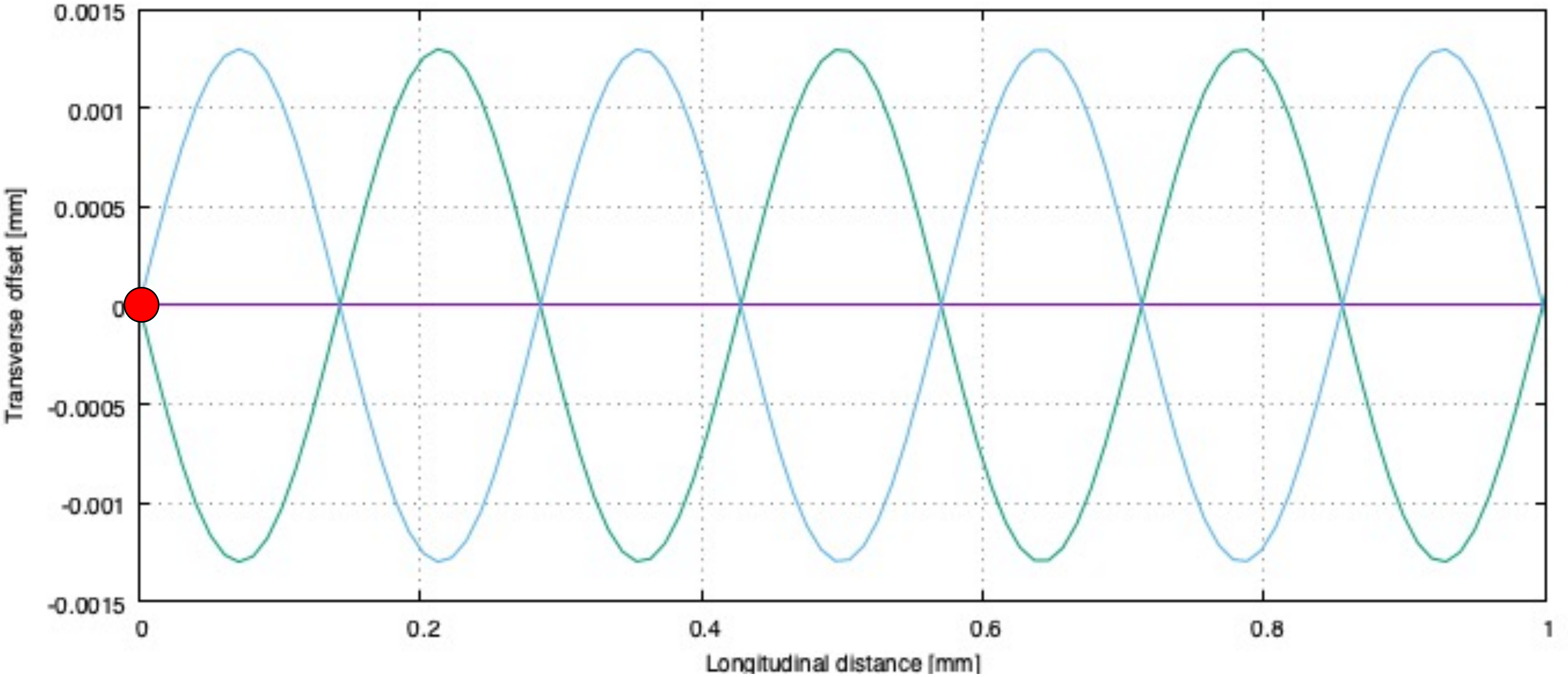


Limits in Energy Spread

Now: Is there an Impact? → Transverse Oscillations

All electrons inside the bunch perform oscillations, assume relativistic electrons → all light velocity



+ 1 σ normalized oscillation amplitude

0 σ normalized oscillation amplitude

- 1 σ normalized oscillation amplitude

Limits in Energy Spread

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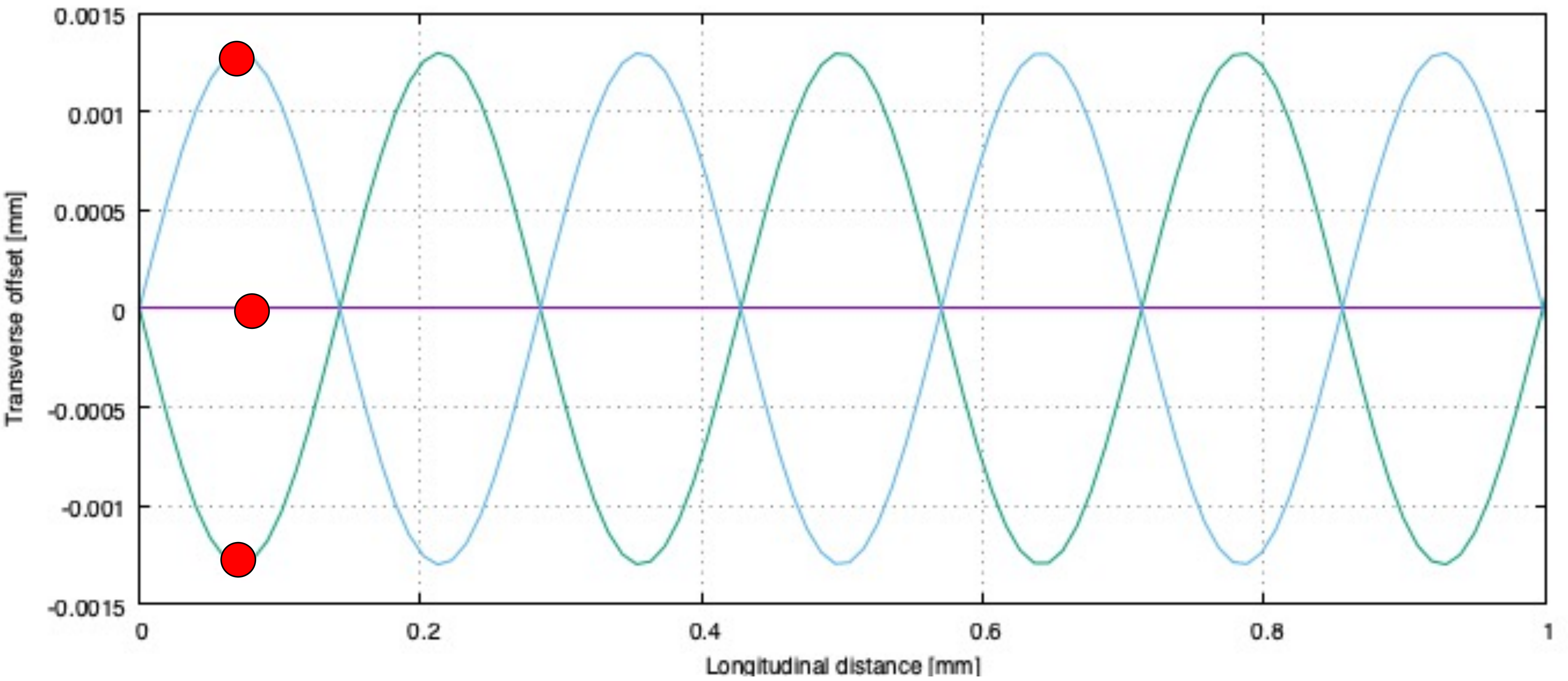

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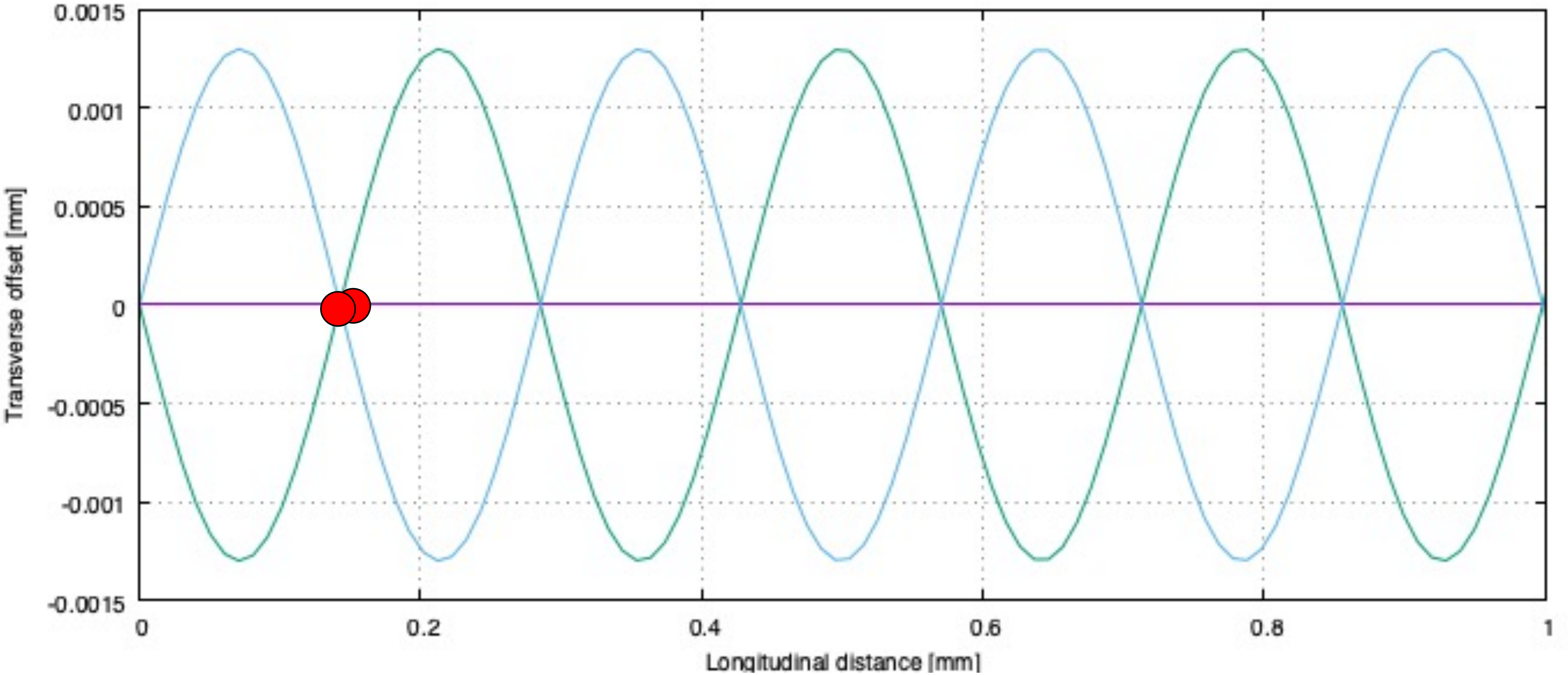

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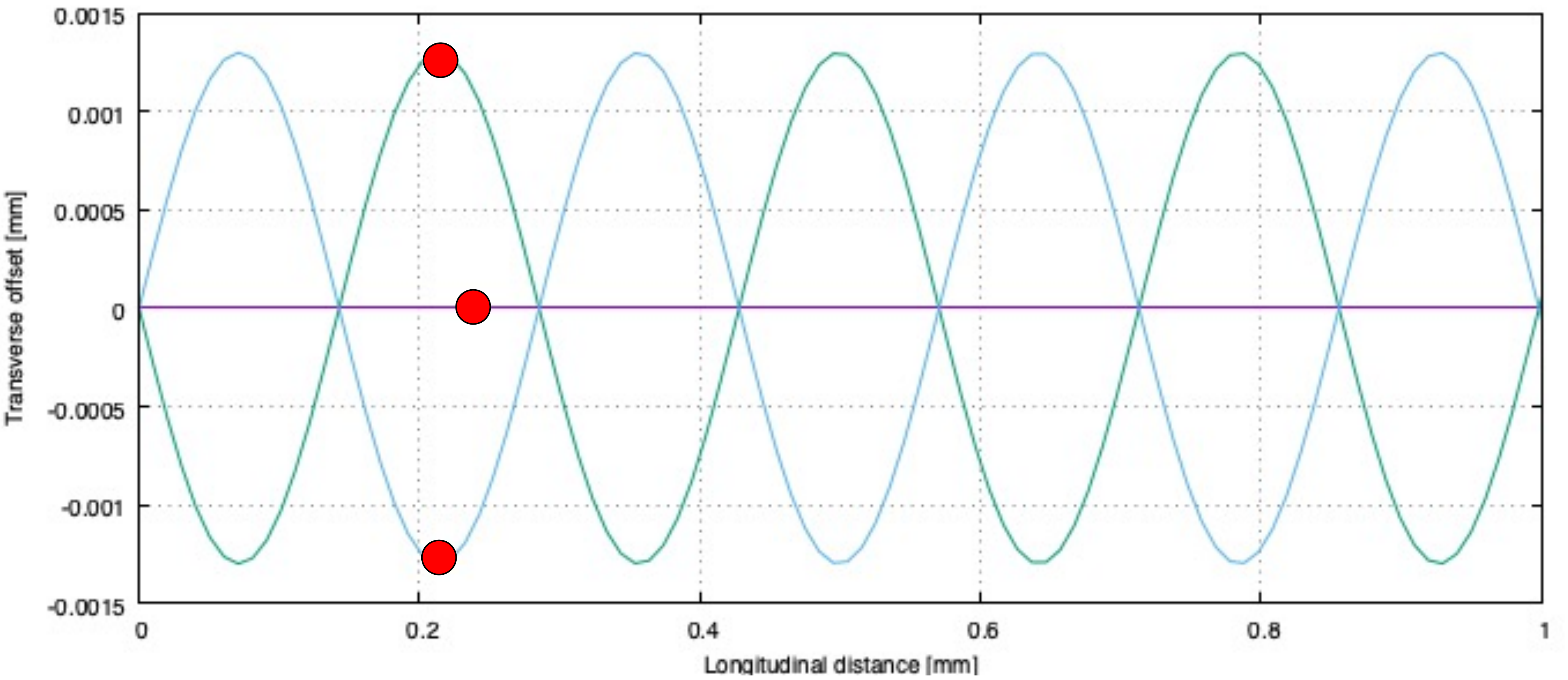


+ 1 σ normalized oscillation amplitude

0 σ normalized oscillation amplitude

- 1 σ normalized oscillation amplitude

Difference in path lengths → large oscillation particles have longer way → fall back and create banana shape

Limits in Energy Spread

Differences in Path Length and Arrival Time

- Usually subtle effects become relevant for plasma accelerators with ultra-strong focusing fields and sub-femtosecond bunch lengths.
- Beam electrons have different transverse oscillation amplitudes A_0 and therefore different path lengths.
- **Consequences**:

Increased bunch length → Correlated energy spread

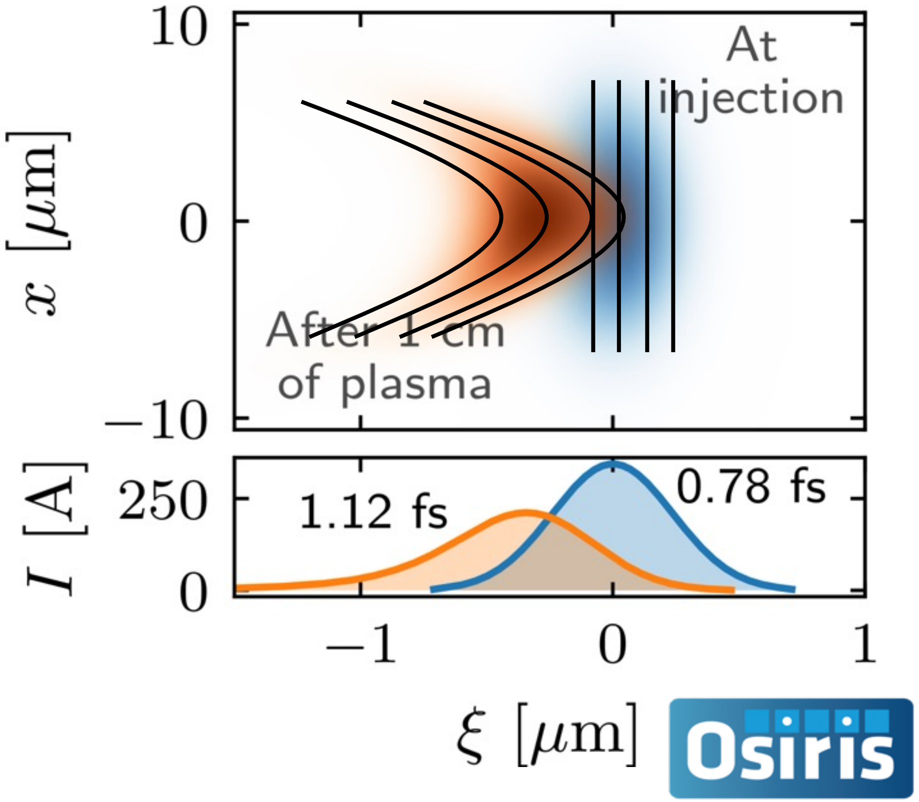
Observed in 2014 by Assmann and Grebenyuk (*IPAC'14*)

Slice mixing → Uncorrelated (slice) energy spread

Relevant for FEL applications

These dynamics were already pointed out by A. Reitsma and D. Jaroszynski, but no further studies (*Laser Part. Beams 2004*)

Here: Development of the first analytical model that describes these effects and limitations accurately for a particle bunch.



Realistic plasma accelerator simulation demonstrating bunch length generation and banana shape

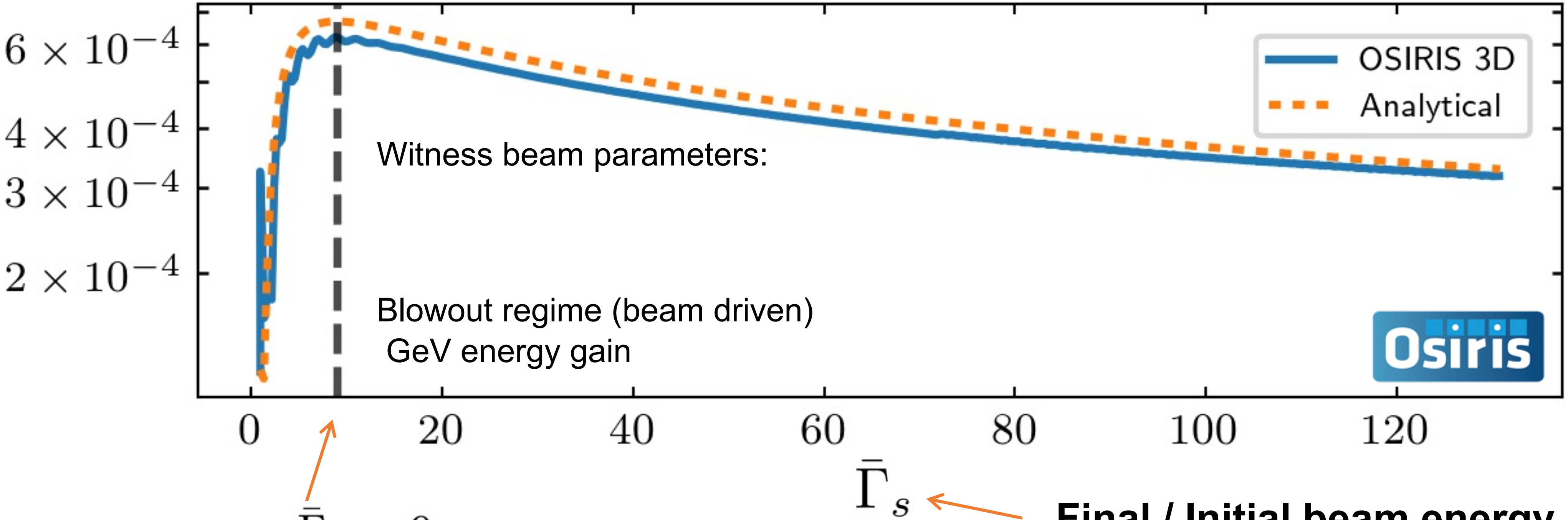
Limits in Energy Spread

Uncorrelated Energy Spread of an Electron Bunch

A. Ferran-Pousan, R. Assmann, et al

- Comparison between analytical model and a full PIC simulation (OSIRIS) for an initial zero longitudinal momentum spread.

Final slice energy spread



Witness beam parameters:

Blowout regime (beam driven)
GeV energy gain

0.05 %

Final / Initial beam energy

Maximum when $\bar{\Gamma}_s = 9$

General rule!

There is always this maximum when the energy is increased by **factor 9**

Excellent agreement with simulations

Limits in Energy Spread

Uncorrelated Energy Spread of an Electron Bunch

Horizon 2020

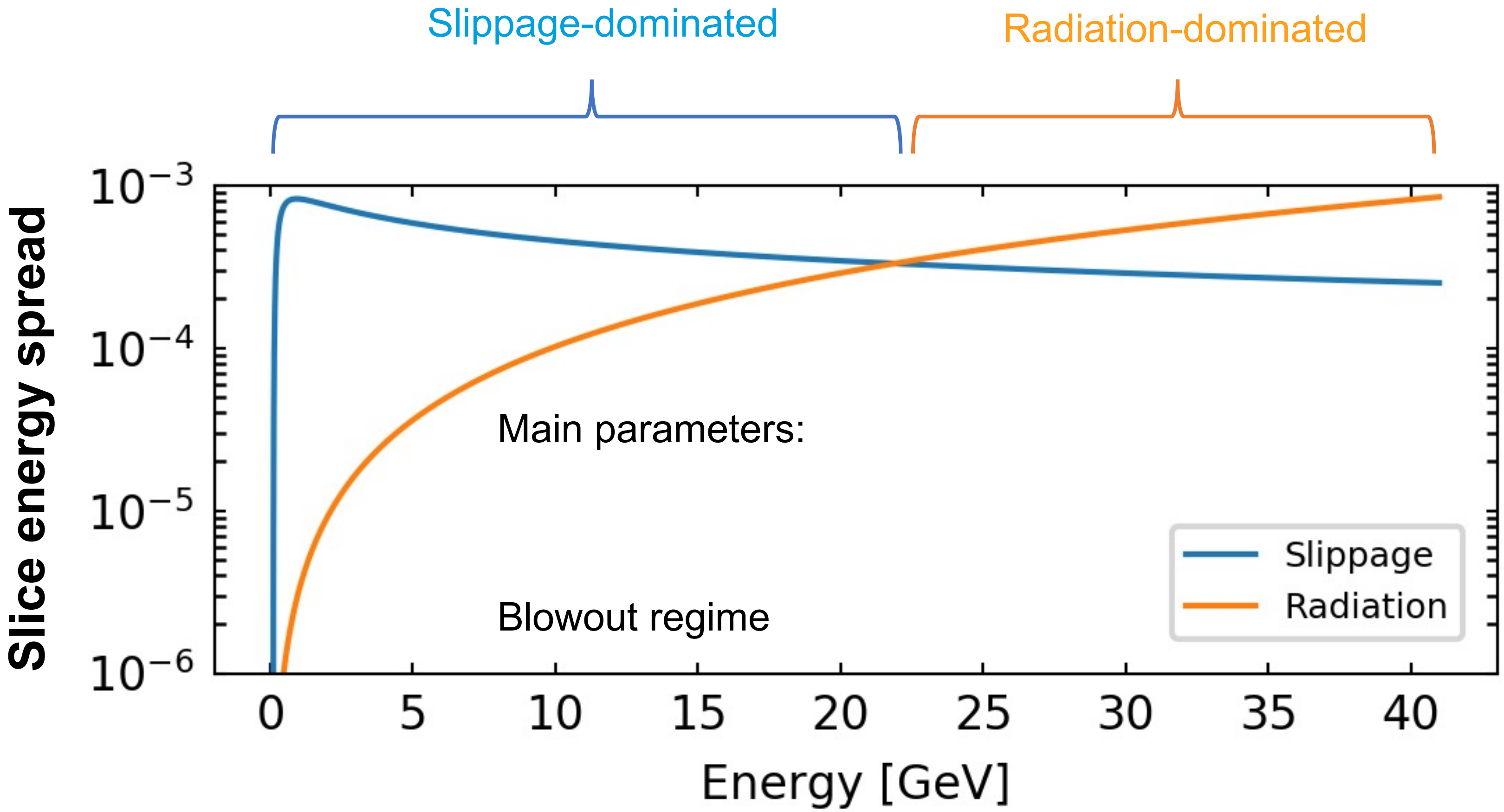
A. Ferran-Pousan, R. Assmann, et al

Betatron slippage

$$\frac{\sigma_{\gamma_s}^{\Delta\xi}}{\bar{\gamma}_s}(t) \simeq \frac{\mathcal{E}'\mathcal{K}\sigma_{A^2}}{2c\mathcal{E}_0^2}\,\frac{\left(\bar{\Gamma}_s(t)^{1/2}-1\right)^2}{\bar{\Gamma}_s(t)^{3/2}}$$

Betatron radiation (P. Michel, 2006, Phys. Rev. E)

$$\frac{\sigma_{\gamma_s}^{\mathrm{R}}}{\bar{\gamma}_s} \simeq \frac{2r_e}{15c^3}\,\frac{\mathcal{K}^2\sigma_{A^2}\bar{\gamma}_{0,s}^2}{\mathcal{E}_0}\,\frac{\bar{\Gamma}_s^{5/2}-1}{\bar{\Gamma}_s}$$



Slippage will typically dominate for energies up to ~10 GeV. **Relevant for FEL applications.**

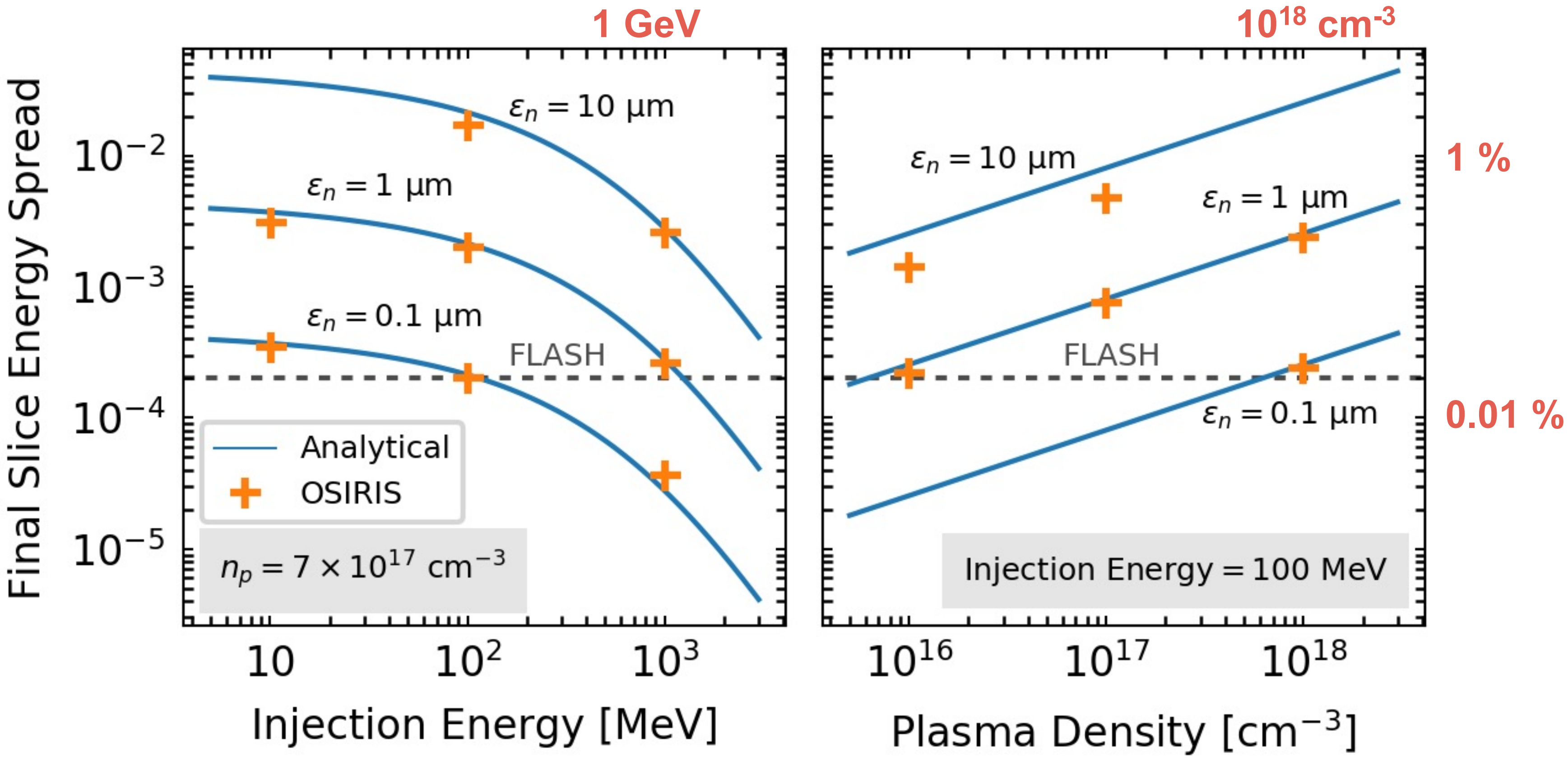
Limits in Energy Spread

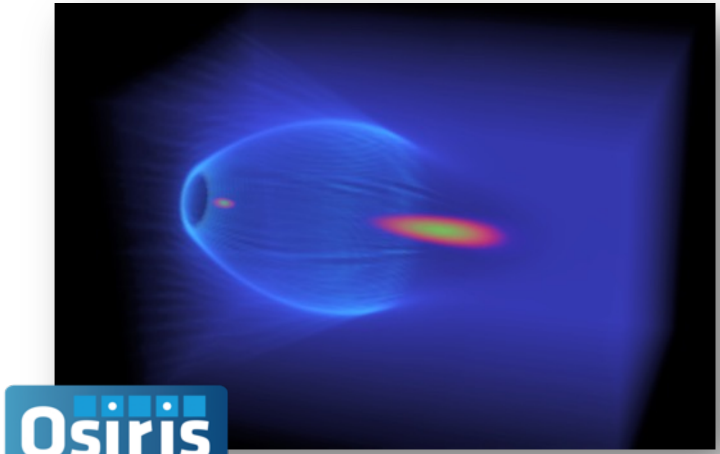
Uncorrelated Energy Spread of an Electron Bunch

A. Ferran-Pousan, R. Assmann, et al

- Test for different **injection energies, emittance** and **plasma densities** on a **1GeV stage**.
- Beam driver.
- Blowout regime.
- Matched witness beam.

$$\sigma_z/c = 3 \text{ fs and } 1 \text{ pC}$$





Made with

Inject with **low emittance**, **high energy**. Use **low plasma density**.

Thank You for Your Attention

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DESIGNING THE FUTURE

The EuPRAXIA Consortium is preparing a conceptual design for the world's first multi-GeV plasma-based accelerator with industrial beam quality and dedicated user areas.

INTERNATIONAL COLLABORATION

EuPRAXIA brings together a consortium of 16 laboratories and universities from 5 EU member states. The project, coordinated by DESY, is funded by the EU's Horizon 2020 programme. The consortium has been joined by 18 associated partners to make additional in-kind contributions.

The consortium holds open international events to strengthen collaborations, to connect to interested users from FEL's, high-energy physics, medicine and industry, and to assess the development of the project.

Computer simulation of a laser wakefield

© Dr Jorge Vieira, Instituto Superior Tecnico, Lisbon

Image of a plasma cell.

© DESY, Heiner Müller-Elsner

Particle accelerators have become powerful and widely used tools for industry, medicine and science. Today there are some 30,000 particle accelerators worldwide, all of them relying on well-established technologies.

The achievable energy of particles is often limited by practical boundaries on size and cost, for example, in hospitals and university laboratories, or available funding for very large scientific instruments at the energy frontier.

A new type of accelerator that uses plasma wakefields promises accelerating gradients as much as 1,000 times higher than conventional accelerators! This would allow much smaller machines for fundamental and applied research.

The goal of this project is to produce a conceptual design for the world's first multi-GeV plasma-based accelerator that can provide industrial beam quality into dedicated user areas.

ADVANCED TECHNOLOGIES

The project is structured into 14 working groups dealing with simulations of high gradient laser plasma accelerator structures, design and optimization of lasers and electron beams, research into alternative and hybrid techniques, Free Electron Lasers (FEL), high-energy physics, and radiation source applications.

EuPRAXIA joins novel acceleration schemes with modern lasers, the latest correction technologies and large-scale user areas. The consortium offers unique training opportunities for researchers in a multidisciplinary field.

OPENING NEW HORIZONS

The project will bridge the gap between successful proof-of-principle experiments and ground-breaking, ultra-compact accelerators.

With a smaller size and improved efficiency, plasma-based technologies have the potential to revolutionize the world of particle accelerators multiplying their applications to medicine, industry and fundamental science.

Participants in the EuPRAXIA Steering Committee Meeting. Paris, February 2016

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